GOOD PRACTICE GUIDE 308

Truck aerodynamic styling

GOOD PRACTICE GUIDE 308

BEST PRACTICE PROGRAMME

ENERGY EFFICIENCY

BEST PRACTICE PROGRAMME

TRUCK AERODYNAMIC STYLING

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GPG 307 Fuel Management Guide

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FOREWORD

This Guide is part of a series produced by the Government under the Energy Efficiency Best Practice Programme. The aim of the programme is to advance and spread good practice in energy efficiency by providing independent, authoritative advice and information on good energy efficiency practices. Best Practice is a collaborative programme targeted towards energy users and decision makers in industry, the commercial and public sectors, and building sectors including housing. It comprises four inter-related elements identified by colour-coded strips for easy reference:

— *Energy Consumption Guides:* (blue) energy consumption data to enable users to establish their relative energy efficiency performance;

— *Good Practice Guides:* (red) and *Case Studies:* (mustard) independent information on proven energy-saving measures and techniques and what they are achieving;

— *New Practice projects:* (light green) independent monitoring of new energy efficiency measures which do not yet enjoy a wide market;

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INTRODUCTION

This Guide offers truck operators practical information on aerodynamically effective trucks and appropriate add-on features.

Typically, the primary function of aerodynamic devices fitted to trucks is to reduce vehicle fuel consumption and, hence, improve cost savings. The majority of this Guide is devoted to helping you predict and realise fuel savings that can be obtained by applying aerodynamic features to your particular truck fleet.

From the outset, it is emphasised that the total savings attainable depend on many fleet-specific factors, a typical example being the annual distance travelled by each truck. Moreover, separate fleets will have differing priorities when selecting aerodynamic features. Such features should be considered within the operational context of your fleet.

This Guide should enable you to:

- evaluate the effectiveness of aerodynamic styling relative to other fuel-saving methods;
- be aware of the range of aerodynamic devices available;
- assess the relevance of sales claims made by manufacturers of add-on aerodynamic features;
- estimate the fuel savings offered by application of aerodynamic devices to your fleet;
- anticipate any secondary effects (either beneficial or adverse) conferred by each of the devices;
- maximise the fuel savings offered by any aerodynamics fitted.

If you require further information on how to manage and save fuel, detailed guidance is available in the Energy Efficiency Best Practice Programm's *Fuel Management Guide*, and a video, available from the Environment and Energy Helpline (0800 585794).

1.1 How this Guide is Organised

- The remainder of this Section gives a brief overview of the range of benefits that are possible from good aerodynamic design. This overview is followed by a comparison of the fuel savings that can be obtained through aerodynamic means and via other methods.
- Section 2 describes some fundamentals of aerodynamics as applied to trucks. This offers an insight into the mechanisms causing aerodynamic drag and a basis on which you can consider the operation of the various aerodynamic devices.
- Section 3 is the most significant part of the Guide. It describes design features to look for in new vehicles and add-on devices that can be used to improve the aerodynamics of these features. Finally, this Section considers the aerodynamic implications of some common vehicle modifications. A summary of the findings is presented in a table at the end of the Section.

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- Section 4 describes some complementary measures that help maximise the fuel savings available from aerodynamic improvements.
- Section 5 includes a brief guide to evaluating the claims of vehicle and add-on device manufacturers.
- Section 6 presents a glossary of aerodynamic terms.

1.2 How to Use this Guide

This Guide and the associated computer spreadsheet give a comprehensive and balanced analysis of the merits of truck aerodynamic features. Fig 1 explains how you should use this Guide to assess aerodynamic add-on devices.

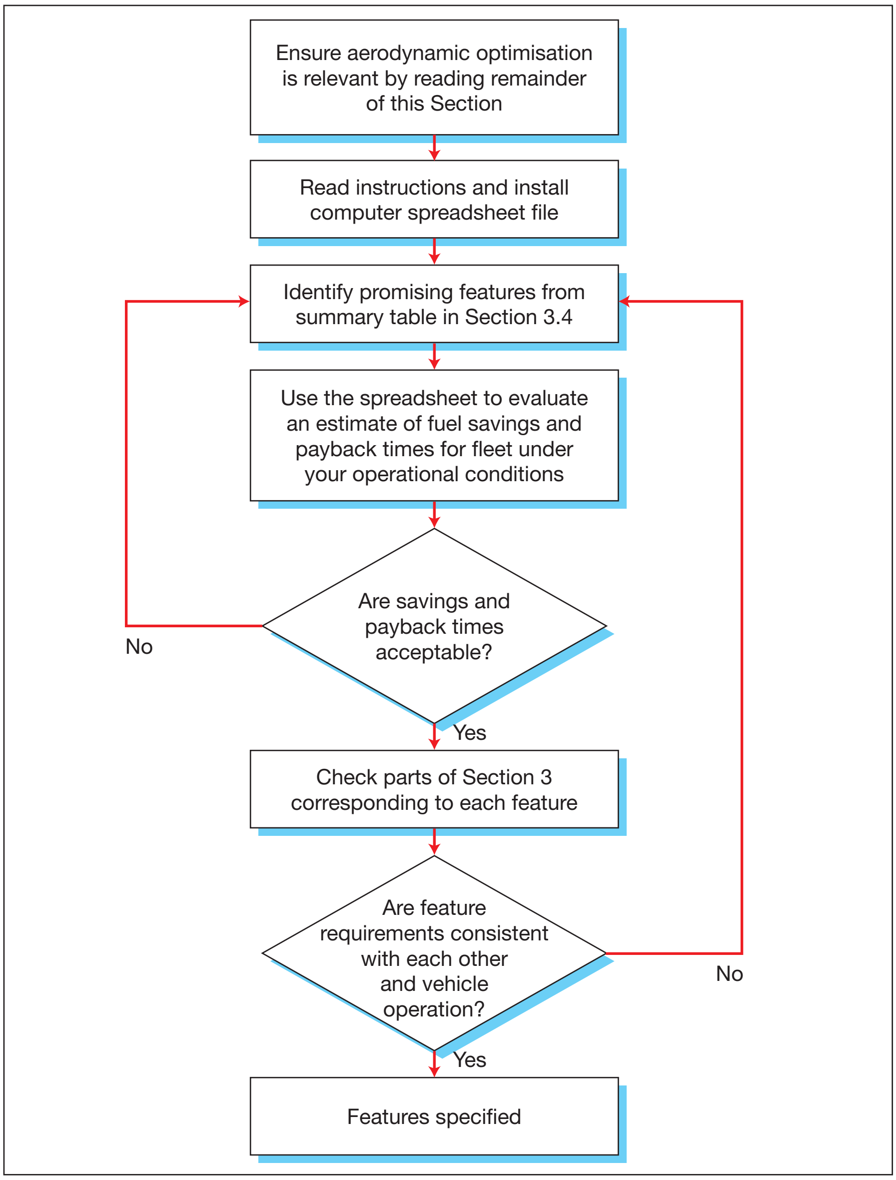

Fig 1 Plan for rapid assessment of add-on devices

Section 3.2 provides advice on the correct adjustment of add-on devices already present on vehicles.

1.3 Fuel Usage of Typical Trucks Due to Aerodynamic Drag

The fuel used by a truck depends greatly on both the characteristics of the vehicle (e.g. mass and frontal area) and, crucially, the route over which the vehicle is operated. This latter factor was typically responsible for the misleading fuel savings

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claims made by manufacturers for aerodynamic optimisation during the late 1970s and early 1980s. It is possible to obtain very substantial fuel savings in a relatively well-defined set of circumstances. In practice, however, most vehicles do not travel exclusively on routes in which these circumstances predominate.

Typically, the fuel used by a commercial rigid truck can be broken down into the main components shown in Fig 2.

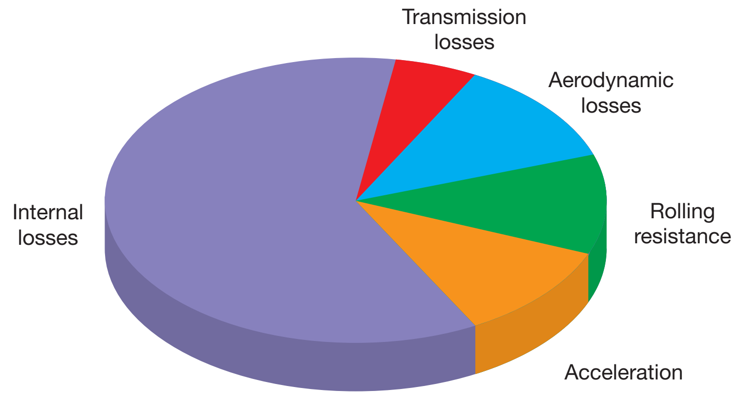

Fig 2 Typical breakdown of fuel used by a truck

The most striking aspect of this chart is that only approximately a third of the fuel used is actually translated into 'useful' mechanical energy at the wheels (i.e. used to overcome aerodynamic and rolling resistance and provide acceleration). This suggests that aerodynamic drag accounts for only a small proportion of the fuel used. If the efficiency of the engine and transmission is constant, however, any reduction in the mechanical work required will reduce the energy losses in these components proportionally. Therefore, the components of mechanical work can be considered as responsible for almost the complete engine fuel usage.

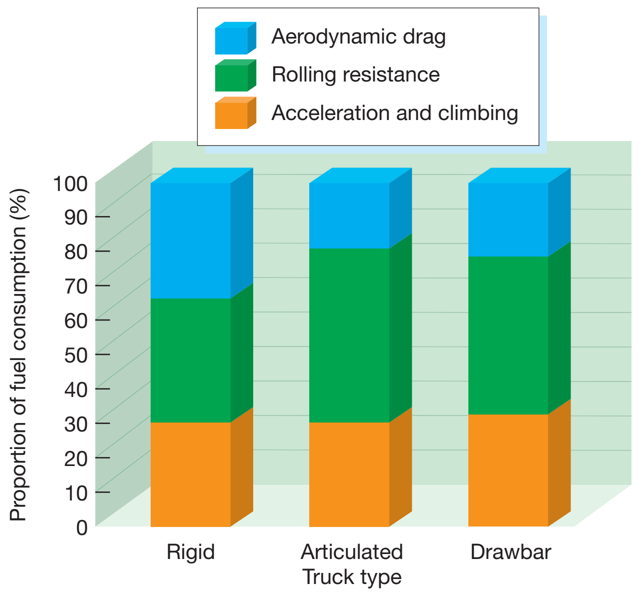

Fig 3 Proportions of fuel consumption associated with tractive forces

Fig 3 estimates the typical fuel consumption contributions made by the forces against which the engine must do work for each generic container truck type in use. While the aerodynamic drag is not necessarily responsible for the largest segment of fuel consumed, it is, nevertheless, significant for each of the vehicle types. The proportion of the fuel consumption associated with aerodynamic drag is, typically, largest for rigid vehicles. However, the lower fuel consumption of such vehicles means that, over a fixed distance, the actual amount of fuel used to overcome aerodynamic drag is similar for each truck type.

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1.4 Benefits of Good Aerodynamics

Good aerodynamics reduce fuel consumption, which saves you money. Recent increases in fuel prices have highlighted the potential fuel savings that can be achieved by add-on aerodynamic drag reduction packages. A vehicle covering 160,000 km (100,000 miles) per annum at 35 litres/100 km (8 mpg) will consume 56,800 litres (12,500 gallons) of fuel. Clearly, even a small reduction in fuel consumption can offer significant cost savings. On average, suitable aerodynamic styling features fitted to a vehicle used on long-distance routes can lower fuel consumption by 6 - 12%, compared to a vehicle with no aerodynamics or badly adjusted features.

Besides the obvious financial advantages, reducing fuel consumption also has the direct environmental benefit of lowering the levels of vehicle emissions produced. In addition, some add-on devices have other benefits, such as:

- spray reduction;
- soiling reduction;
- improved vehicle performance at high speed;
- often a reduced sensitivity to side winds;
- improved vehicle appearance.

1.5 Aerodynamic Styling and other Fuel-saving Methods

Aerodynamic drag reduction is just one of a diverse array of approaches to saving fuel. Other methods range from driver training and incentives, to use of low viscosity gearbox oils, to installation of separate cab heaters. Most of these techniques are complementary - the more methods employed, the more fuel may be saved.

Generally, it is unlikely there will be sufficient resources available to implement all of these fuel-saving measures simultaneously. In such cases, you need to identify both the most effective approaches and the point where the fuel savings from each become subject to diminishing returns.

When comparing alternative measures for achieving fuel savings, you should consider the following questions:

- How large are the fuel savings that my fleet can expect to achieve?
- How much will it cost to implement?
- How much will it cost to maintain?
- What is its lifespan?
- Are there any other benefits?
- Does this restrict the operation of my fleet in any way?

The answers to the first three questions can be neatly summarised by two quantities: the initial financial outlay and the overall savings rate. For aerodynamic add-ons, the initial financial outlay can be readily calculated from the price supplied by the vendor. The overall savings rate can be determined using the information in Section 3.2 together with the spreadsheet program. Some nominal values for the cost of each device are presented in Section 3.4.

1.6 When is Aerodynamic Styling Most Effective?

The potential for fuel savings through a reduction in aerodynamic drag increases when the energy needed to overcome the aerodynamic drag is initially large. Some of the factors that increase the fuel consumption associated with the aerodynamic drag are given below.

- **High speed travel**

  The aerodynamic drag force against which the engine must work depends strongly on the vehicle speed. Therefore, vehicles spending a large proportion of time at high speed offer the greatest scope for fuel savings.

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To highlight this, Fig 4 shows the resistance forces that a 10-tonne rigid vehicle must overcome over a range of cruising speeds. The dependence of the fuel consumption on cruising speed will display a similar overall trend.

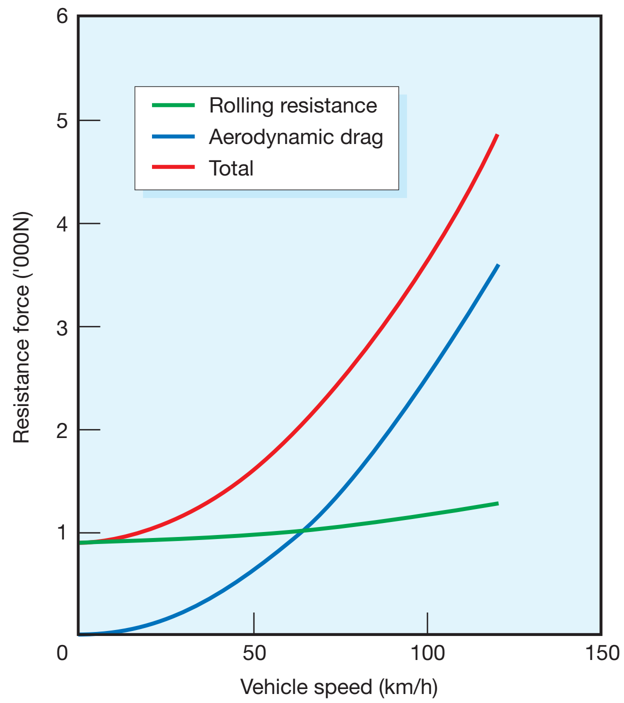


Fig 4 Resistance forces created at various speeds

Fig 4 demonstrates that, at a constant 50 km/h (30 mph), less than 40% of the useful available energy from the engine will be used to overcome aerodynamic drag, while at 95 km/h (60 mph) this proportion rises to over 60%.

- **Large vehicle frontal area**

  For a given vehicle shape, increasing the vehicle frontal area will increase the aerodynamic drag, as will be explained in Section 2.1. Consequently, improving the shape gives a larger fuel saving.

- **Poor initial aerodynamic design**

  A poor initial aerodynamic design increases the overall vehicle drag, which suggests that substantial improvements may be readily achieved.

Due to aerodynamic drag, the factors above actually increase the size of the fuel bill. However, there are some further factors that increase the relative importance of aerodynamics by reducing the fuel consumed due to other resistance forces:

- **Low acceleration**

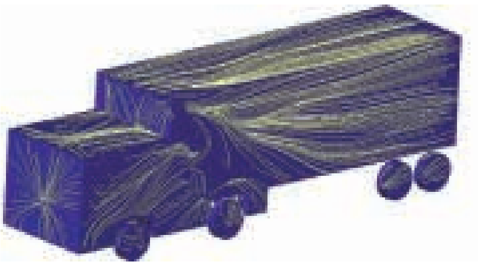
  Travelling at a speed that is as constant as possible on level roads ensures that minimal fuel is being used to accelerate the vehicle.

- **Low mass**

  A low vehicle mass decreases both the rolling resistance of the vehicle and the energy it requires to climb hills and accelerate on level roads.

In relative terms, the above points highlight that aerodynamics are most important in situations where large, light vehicles are travelling at a high, constant speed in an exposed environment. Saving fuel through aerodynamic improvement is, therefore, achieved most readily on motorways and least readily in a hilly or urban environment.

2 AERODYNAMICS - BASICS



This Section presents an introduction to aerodynamics, which serves as background information to the descriptions of individual aerodynamic features that follow in Section 3. You will be able to find more detailed information in Appendix A.

2.1 Aerodynamic Drag

When a vehicle moves through air, the air exerts a force on the vehicle that opposes its motion. This force is the aerodynamic drag.

The aerodynamic drag force on a vehicle is composed of the contributions below.

- **Form drag**

  In motion, the pressure on the parts of the vehicle facing forwards is greater than on those facing backwards. The areas over which these pressures act give rise to an overall force that opposes the direction of vehicle motion. This force is known as the form drag, or the pressure drag. For commercial vehicles, this is the dominant source of aerodynamic resistance; typically, it accounts for over 80% of the drag.

  Form drag is caused mainly by flow separation. At separation, air that was flowing parallel to the sides of a body upstream is unable to continue to do so. The location at which the air 'breaks away' from the body is called the separation point. Downstream of separation, the airflow pattern typically rotates ('eddies') in an unsteady manner; this motion dissipates energy. If the air separates before the rear of the body, it is possible that the airflow can re-attach to the body sides and continue to follow the contours of the body shape downstream.

  Fig 5 highlights some of these features for a simplified block shape. The 'lines' represent the paths that will be taken by the air; these are referred to as streamlines.

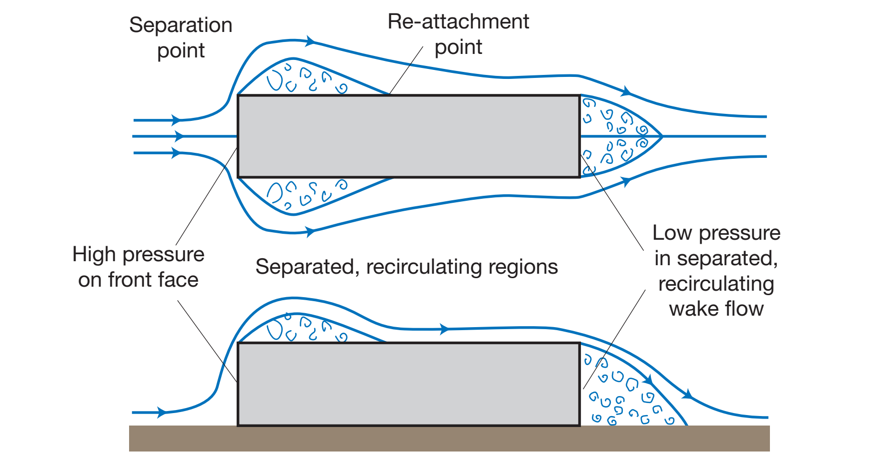


Fig 5 Streamline diagram

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- **Skin friction drag**

  The air in immediate contact with the vehicle surface must move at the same speed as the vehicle, while, in the absence of wind, the air much further away is at rest. Since air is viscous, this relative air movement results in a shear force that acts on the vehicle surface. The portion of this force that acts backwards is the skin friction drag. Usually, this source of drag only becomes significant as the shape becomes more streamlined.

Drag coefficient

The aerodynamic drag force is related to the **drag coefficien**t of the vehicle, as shown below:

Aerodynamic drag = Drag coefficient x Frontal area x Wind pressure

The drag coefficient is usually denoted by either 'Cd' or 'C_D' and corresponds to wind incident on the vehicle from a particular direction. Broadly, in this expression the drag coefficient represents the effect of the vehicle shape on the drag force, the frontal area represents the effect of the size of the vehicle, and the wind pressure represents the effect of the vehicle speed.

The wind pressure is a measure of the kinetic energy within a unit volume of air. It is defined as follows:

Wind pressure = $^1/_2\ \rho\ V^2$

In this expression, ρ (pronounced 'roe') is the density of the air (a value of 1.2 kg/m^3 is typically a good estimate) and V is the speed of the air relative to the vehicle (which, in the absence of any environmental wind, is numerically equal to the speed of the vehicle relative to the ground). It is important to note that the wind pressure depends on the square of the air speed. This means that, at high vehicle speeds, even a small increase in incident air speed corresponds to a relatively large increase in wind pressure and, hence, aerodynamic drag.

To estimate the average aerodynamic drag force at a given vehicle speed, which incorporates the average effect of atmospheric wind, the drag coefficient in the expression above may be replaced by the wind-averaged drag coefficient (Cd_{ave}). The origin of this term is explained more completely in Appendix A.1. Here, it is sufficient for you to understand that the term offers the best estimate of the average aerodynamic drag force experienced by the vehicle at a particular speed.

Drag coefficients have received substantial attention in the media (mainly for the purpose of advertising cars). Strictly speaking, however, the aerodynamic drag force depends on a combination of the drag coefficient and the frontal area, at a given vehicle speed (as shown in the expression above). Therefore, a reduction in frontal area that does not alter the drag coefficient will reduce aerodynamic drag. A limited number of measures are available to reduce the frontal area of the vehicle. These are outlined below.

- **Avoid excessive container sizes**

  Protruding empty parts of the container can increase the drag unnecessarily. Therefore, you should give some consideration to the maximum cargo **volume** that will be required.

- **Use a small cab if possible**

  The size of the cab will dominate the frontal area of both trucks without a container and tractors of articulated units run in isolation. For other configurations, there is usually little aerodynamic benefit from restricting the cab width to below that of the container.

- **Consider dense packing**

  For trucks without containers, loads should be constrained to lie within the frontal area of the cab wherever possible. Usually, this also reduces the drag coefficient.

Racing car with transporter. The transporter has a lower drag coefficient (perhaps as low as half of that of the racing car) but, at a given speed, the racing car will experience a lower aerodynamic drag force by virtue of its much smaller frontal area.

In practice, the frontal area of container vehicles is usually dominated by the size of the containers themselves, so there is little scope for reduction of the vehicle frontal area. Table 1 offers some characteristic areas and drag coefficients for each of the major vehicle types under consideration.

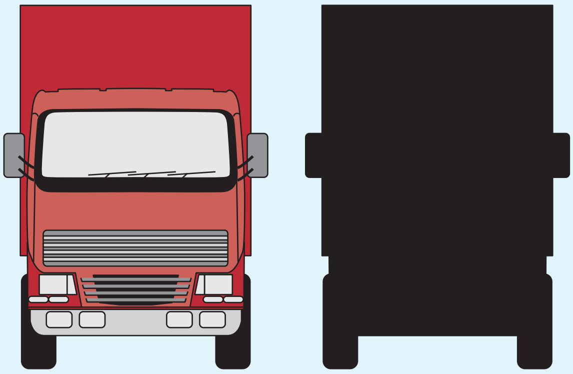
	Typical frontal area (m^2)	Typical wind-averaged drag coefficient
Rigid	8.75	0.7
Articulated	9.5	0.85
Drawbar	8.75	0.9

Table 1 Typical values of frontal area and wind-averaged drag coefficient for vehicle types

Note that the frontal area of each vehicle type is dominated by the contribution of the container element, and that this may vary from vehicle to vehicle. Therefore, it is recommended that the frontal areas used to predict fuel savings reflect those of the vehicles in your fleet.

How to estimate frontal area

To obtain a value for the frontal area of container vehicles that is sufficiently accurate for predicting fuel savings, multiply the width of the container and the height of the container roof from the ground. This will give you a reasonable estimate of the outer area. From this, the product of the ground clearance and the distance between the inside of the tyres should be subtracted to obtain the overall area estimate. The rationale for this is immediately apparent from the vehicle silhouette below.



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2.2 Airflow Around a Typical Truck

Fig 6 shows the airflow pattern around a simplified version of an articulated vehicle having a poor aerodynamic design, in windless conditions.

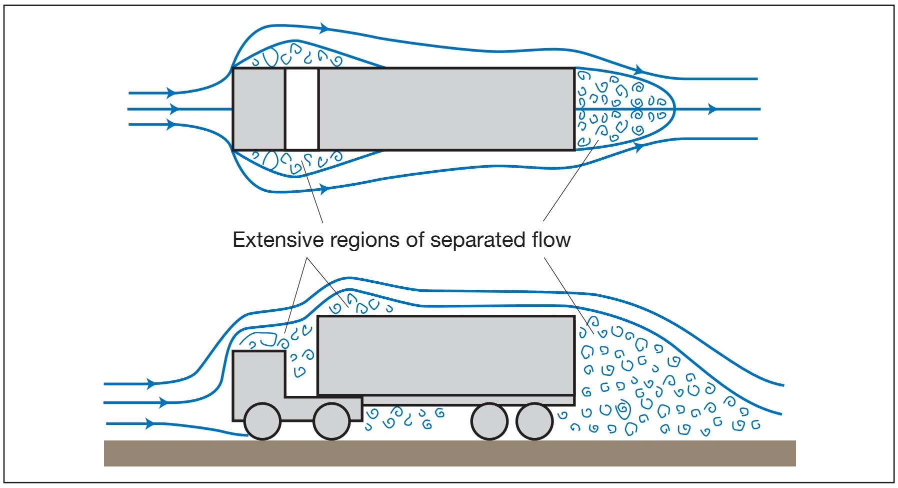

Fig 6 Typical airflow pattern around an unaerodynamic truck

The extensive flow separation from the side edges at the front of the vehicle can be associated with substantial pressure drag. This separated region constitutes a potential safety hazard, e.g. for cyclists.

To reduce the aerodynamic drag, the shape of the vehicle must be changed to minimise these separated flow regions. This process is called **streamlining**. Ensuring that the flow remains attached will also reduce the level of buffeting experienced by nearby cyclists. Fig 7 presents the comparative flow pattern around a more streamlined truck.

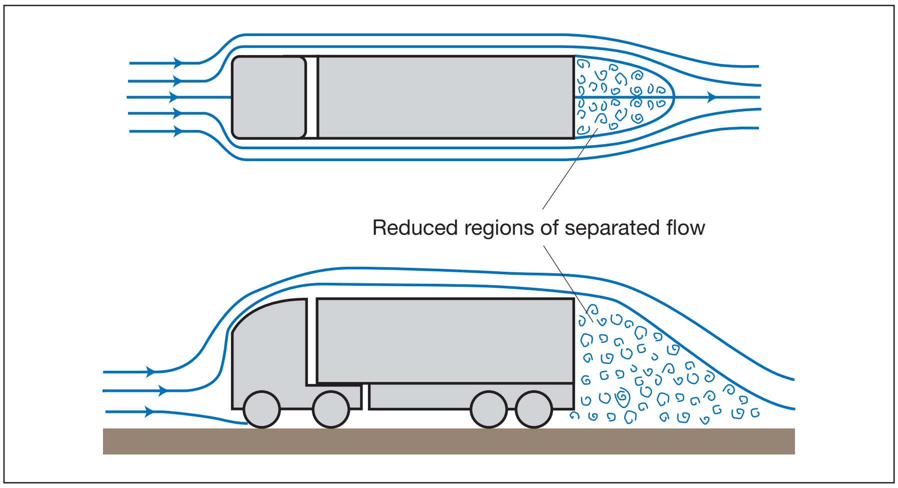

Fig 7 Typical airflow pattern around an aerodynamically effective truck

The substantial alteration of the airflow around the vehicle is of particular note. This can be achieved by relatively small modifications to the vehicle geometry - in this case a modest radius to the front and side edges of the cab.

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3 AERODYNAMIC FEATURES

3.1 Aerodynamic Drag of a Basic Vehicle

This Section describes the influence of some key, basic design features on the aerodynamic performance of the vehicle; Section 3.2 describes possible add-on features.

Cab front edge rounding

Often overlooked, the front edges of the cab can have a substantial influence on the aerodynamic drag of the vehicle and the operation of add-on aerodynamic devices. The drag coefficient changes that can be achieved by rounding the front edges of the vehicle depend strongly on the geometry of the remainder of the vehicle. The side edges of most modern cabs below the windscreen level can be regarded as already 'rounded'. For some vehicles, however, the side edges above the level of the base of the windscreen and/or the roof edges can be inadequately radiussed and will behave, largely, as though they are 'sharp'.

Relative merits for drag reduction

Benefits

- A rounded front roof edge can reduce drag in many cases.
- Rounded front edges also combine favourably with cab roof deflectors and fairings to enhance the drag reducing effects and, therefore, the overall saving.
- Rounded side edges also help to decrease the drag of the cab.
- **For a tractor unit alone,** rounded front edges of the cab can prevent flow separation and reduce the overall drag coefficient from above 1.15 to around 0.60.

Limitations

- In a particular set of circumstances (outlined in the notes opposite) it is preferable for the front roof edge to be sharp.
- For rounded side edges, a balance must be struck between the drag reduction offered and the decrease in directional stability.

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Design/purchasing notes

- **When the front roof edge should not be rounded**

  In most situations, radiussing the front roof edge will prove beneficial. For a **sharp** roof edge to be advantageous, all of the following circumstances should apply:

  - The truck is not used with a roof deflector or fairing.
  - The truck is run with a container in place for the majority of the time.
  - The container roof height is at least 20% greater than the height of the cab.

- **How large a radius is necessary?**

  - The minimum radius necessary actually depends on the vehicle speed above which the drag reduction is to be obtained. As a guide, a radius of 150 mm (6 in) should be sufficient to obtain the drag reduction over all speeds for which aerodynamic forces are significant. A radius of 75 mm (3 in) should, however, be sufficient to obtain the available drag reduction at speeds of 80 km/h (50 mph) and above, where aerodynamic resistance starts to predominate.
  - For edges with changing radius, it is probably the minimum radius value that should be considered.
  - Water gutters and drip features that are sharp-edged and located close to the edge of the cab roof may induce unwanted separation, with a resulting increase in drag coefficient. Therefore, these features should be as rounded as possible and located away from the edges of the roof if edge rounding is to prove wholly effective.

Cab/container gap minimisation

A large gap between cab and container can increase the drag coefficient significantly. For articulated and drawbar vehicles, this is one of the main aerodynamic improvements that can be achieved without the use of add-ons.

Relative merits for drag reduction

Benefits	Limitations
• Substantial drag reductions. • Effective in crosswind conditions. • Drawbar trucks benefit considerably from minimising the gap between the lead vehicle and the trailer. The straight-line drag can decrease by as much as a third if the front of the vehicle has been optimised, and even more in a crosswind. • The drag of rigid vehicles is also reduced but by a much smaller amount.	• Drag reductions will not be so great if the vehicle has a cab roof deflector or fairing, or side fairings, or the container has a frontal fairing.

Additional benefits

- Improved stability in crosswind conditions.
- Close-coupling offers increased potential load volume, without exceeding legal length limits.

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Adjustment/operational details

- A minimum practical gap width is imposed by:
  - manoeuvrability requirements;
  - the need to access the rear of the tractor or the drawbar linkage.
- For articulated vehicles, the weight transfer onto the tractor axles caused by minimising the gap can have an adverse effect on the steering weight.

Cab/container height equalisation

If the front roof edge of the cab is rounded, a closer match between cab and container heights will reduce the drag coefficient. If a lower container is used to achieve this aim, further drag savings will be obtained from the reduced frontal area of the vehicle.

Relative merits for drag reduction

Benefits	Limitations
• Avoids the drag penalties caused by large step changes in frontal area. • If used in conjunction with a reduced cab-container gap width, a significant improvement in aerodynamic performance is possible.	• Unnecessary if a suitable deflector or fairing used. • Less flexible than adjustable cab roof fairings or deflectors. • As the cab height is increased relative to the container, the optimum front edge treatment changes. • Increasing the tractor height of articulated vehicles to match that of the trailer can result in drag increases if the tractor is used subsequently with a smaller container, or in isolation.

Additional benefits

An increased cab height offers scope for increased storage or a sleeping area.

Design/purchasing notes

- Circumstances in which each edge treatment is preferable are described in Appendix A.2.
- Differing cab sizes can be used in conjunction with small cab roof deflectors or fairings for ‘fine tuning’ purposes. However, the fuel savings achievable for this combination may be no better than those achieved for a roof fairing.
- For articulated cabs with rounded edges, the minimum aerodynamic drag is actually obtained when the cab exceeds the height of the container slightly (by approximately 0.1 m for typical container sizes).

3.2 Aerodynamic Drag Reduction Features

This Section describes the aerodynamic effects of features that can be justified solely for the drag reduction benefit they offer.

For each feature, the typical levels of drag reduction for three generic truck types have been quantified. You should consider the drag reductions presented as indicative rather than absolute. Some devices offer a broad range of savings depending on the particular design, and the savings achieved by a single device may depend on the truck shape.

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The absolute benefit of each aerodynamic modification depends on the design of the original vehicle, correct use and adjustment, and the particular arrangements in which it is used. The correct selection of add-on features is crucial to extracting the maximum fuel-saving benefit, and an inappropriate combination or adjustment of add-ons can even increase the fuel consumption.

It is essential that the add-on features that you choose are appropriate to the vehicle design and complementary to one another. The following pages provide a guide to the benefits and disadvantages of several of the most common and most effective aerodynamic add-ons.

The fuel savings that can be achieved from these drag reductions depend strongly on the manner in which the fleet is operated (as discussed in Section 1.3). Therefore, it makes sound commercial sense to predict the fuel savings that your fleet could achieve, prior to any purchase or modification. You can do this by studying the nominal savings for the example cases presented, or, preferably, by using the supplied spreadsheet program (see Appendix B for instructions).

Assumptions for calculating fuel savings and payback times

The performance of each feature for aerodynamic drag reduction is described by the estimate for the wind-averaged drag coefficient reduction.

- The initial drag coefficients and frontal areas have been taken as equal to the typical values shown in Section 2.1 – Table 1.
- An annual mileage of 160,000 km (100,000 miles) has been assumed for all vehicles.
- Fuel consumptions of 28 litres/100 km (10 mpg) for rigid vehicles and 40 litres/100km (7 mpg) for articulated and drawbar vehicles have been assumed.
- Engine power outputs of 200 kW for rigid vehicles and 350 kW for articulated and drawbar vehicles have been used for the analyses.
- To assess the total savings, a fuel price of £0.80/litre has been used. The payback time for each aerodynamic feature incorporates interest on initial expenditure at 10%, but does not include allowance for the value of any loss of payload resulting from the mass of the feature.

For the same driver in a vehicle with a prescribed drag coefficient, the variables, which perhaps exert the most significant influence on the fuel savings predictions, are the types of route the vehicle travels over and the mass of the vehicle. To provide maximum insight into the fuel savings obtained by each feature, Table 2 lists the three sets of predictions that have been made for each vehicle type:

- Case A - a ‘baseline’ analysis.
- Case B - a configuration with reduced vehicle mass running on the same route.
- Case C - a configuration with the same mass as the ‘baseline’ case but running on a more urban route.

	Case A	Case B	Case C
Vehicle mass (tonnes)			
Rigid	17	10	17
Articulated	40	32	40
Drawbar	40	32	40
Route composition (%)			
90 km/h (56 mph)	40	40	30
Undulating motorway	20	20	20
Typical A/B road	20	20	20
Mountainous	5	5	5
Urban	15	15	25

Table 2 Scenarios of vehicle mass and route composition

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There is one further important assumption on which the fuel savings estimates have been based; namely, no fuel savings are accrued over portions of the route with variable speed.

When estimating the percentage fuel savings for a particular scenario, the reduction in drag coefficient provided by each add-on feature can be considered cumulative (except where explicitly stated otherwise). While this may not always be strictly true, simply adding the reductions together does give a useful indication of the likely benefit, without the need for vehicle-specific wind-tunnel testing. Therefore, for vehicles that already have some aerodynamic add-on devices, you need to modify the basic drag coefficients according to the features already present on the vehicle.

Description of Add-on Devices

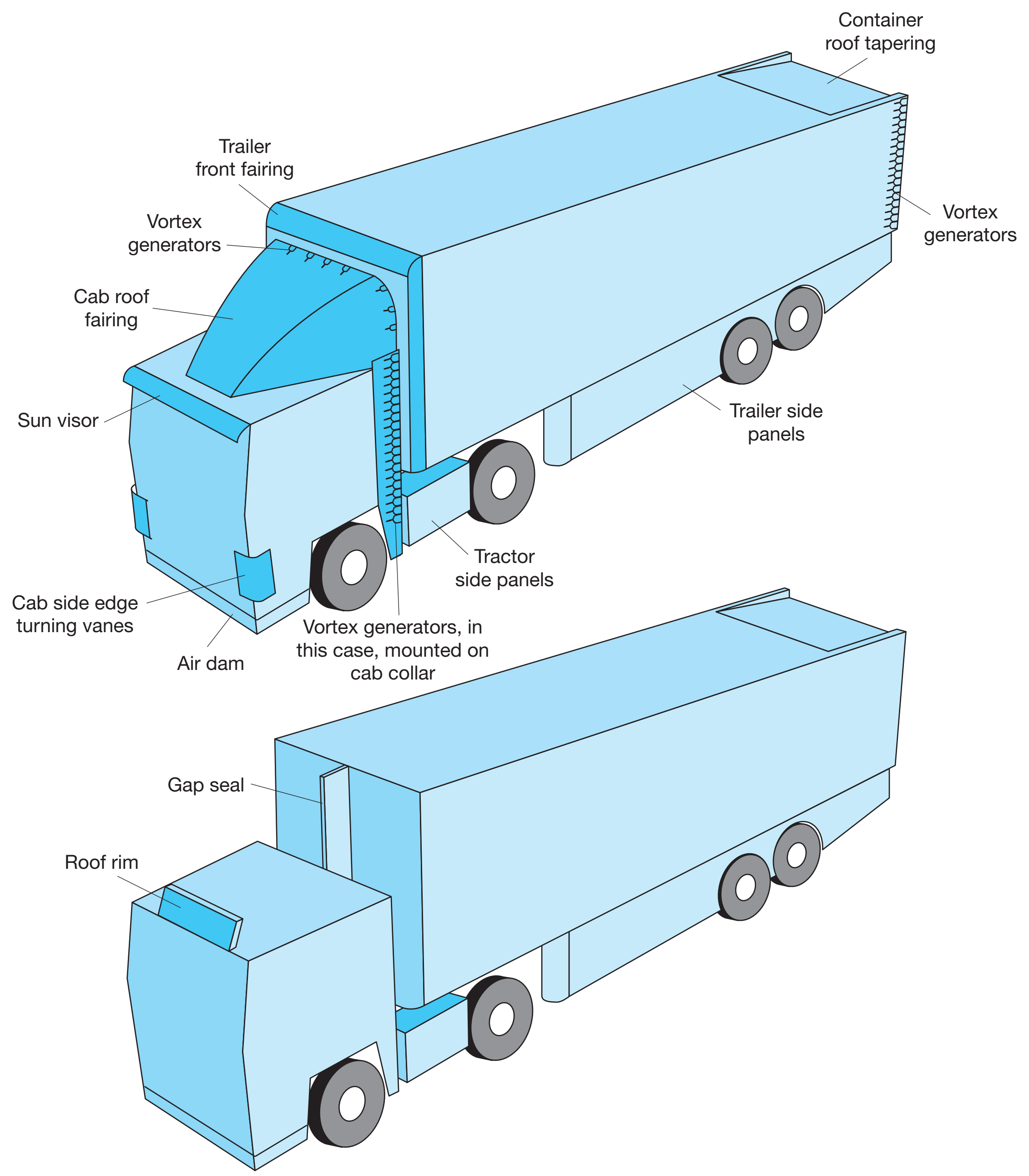

Fig 8 Schematic depiction of aerodynamic features on an articulated vehicle

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Cab side edge turning vanes

These are small extension pieces, typically located on the cab front edges below the level of the windscreen. Generally used to reduce dirt deposition on the door, they can also reduce the vehicle drag if the local edges were originally sharp.

Relative merits for drag reduction

Benefits	Limitations
• Can provide slight drag reduction if the cab edges are sharp or have small radius.	• Can increase the drag if the cab edges are already well rounded.

Additional benefits

Suitably located vanes can reduce soiling in those regions immediately downstream, e.g. the cab side windows and/or doors. In practice, this reduction in dirt deposition is normally the primary reason for purchase. Consequently, there are two potential advantages:

- Improved safety

  Clean side windows offer safety benefits, as the driver's view of the external mirrors is not obscured.

- Improved cab appearance

  The cab should stay cleaner for longer and, therefore, may require washing less frequently.

Purchasing notes

- To ensure that the flow remains attached around the exterior of the vane, the minimum outer radius of the vane should be at least 75 mm, or about 3 in.
- If the vanes are to prove as effective as possible for keeping the cab clean, the struts spacing the vane from the vehicle should present minimal blockage for the air flow between the vane and the vehicle body.
- The front side edges below the level of the windscreen are normally sufficiently rounded to prevent flow separation, so there is little scope for drag reduction in these regions. Conversely, the edges adjacent to the cab windscreen are typically less rounded. These sections of the edges may also possess gutters, etc. that will encourage the adjacent airflow to separate. Therefore, there may be more scope for drag reduction if the features are located in these areas, although, for most modern vehicles, this region is radiussed adequately.
- Make sure that loss of visibility is negligible when considering vanes for the windscreen edge.
- If the load is likely to be wider than the cab, it is probably not beneficial to fit turning vanes.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Rigid	-0.02	100	0.5	0.7	0.6	0.5	0.3	0.9
Articulated	-0.02	100	0.3	0.7	0.4	0.6	0.2	1.0
Drawbar	-0.02	100	0.3	0.7	0.3	0.7	0.2	1.1

Note: Based on vehicles for which the edge radiussing is sufficient to ensure attached flow below the level of the windscreen but inadequate adjacent to the windscreen.

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Air dam

Air dams are smooth downward extensions of the bumper towards the front wheels at a level close to the ground. They operate by forcing air to pass over the more aerodynamic side and upper surfaces of the vehicle rather than the rough underbody. Most modern vehicles are already fitted with air dams.

Relative merits for drag reduction

Benefits	Limitations
● Significant drag reductions in calm conditions for rigid and drawbar vehicles. ● Drag reductions not duplicated by other features.	● Drag reductions diminish in crosswind environments. ● May increase drag for articulated vehicles. ● Less effective as truck length increases.

Purchasing notes

- Deeper air dams are more effective because they divert more of the flow around the sides and top of the tractor. However, a compromise is necessary to avoid grounding, so air dams are typically located close to the front axle.
- Simple downward extensions of the bumper (as seen on many cars) do not appear to be as effective.
- Air dams, as with other low-level parts of the vehicle, are susceptible to damage from stone chips. Therefore, it is worthwhile considering a dark colour-impregnated device.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Rigid	-0.03	250	0.7	1.0	0.9	0.9	0.5	1.5
Articulated	-0.02	250	0.3	1.7	0.4	1.6	0.2	2.7
Drawbar	-0.02	250	0.3	1.7	0.3	1.7	0.2	3.0

Note: Drag reduction for articulated truck assumes that the vehicle is a container truck. Drag reductions will be achieved for tankers and flatbed vehicles.

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Cab roof rim

A roof rim constitutes a raised piece extending almost vertically from the front roof edge. It is normally used for the principal purpose of highlighting the operator's name on the front of the vehicle. Nevertheless, it is capable of exerting a strong influence on the airflow pattern above the cab roof and having a corresponding effect on the drag coefficient. This effect is normally detrimental but, in certain situations, there can be an improvement in the wind-averaged drag.

Relative merits for drag reduction

Benefits

- Drag reductions in circumstances where a sharp roof edge is beneficial.

Limitations

- Drag increases in circumstances where a rounded roof edge is beneficial.
- Always increases drag in the absence of a container.
- Drag reductions diminish in crosswind environments.
- Incompatible with other types of cab roof fitting.
- Less effective than other types of cab fitting.
- Not usually adjustable, although drag reduction does depend on height.

Additional benefits

The device provides a natural location for the operator's name or other advertising - this is usually the primary reason for purchase.

Purchasing notes

Only really beneficial for cabs with sharp front roof edges.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Rigid	-0.04	100	1.0	0.3	1.2	0.2	0.7	0.4
Articulated	-0.10	100	1.5	0.1	1.8	0.1	1.1	0.2
Drawbar	-0.04	100	0.5	0.4	0.6	0.3	0.4	0.5

Note: Drag reductions relate to maximum values achievable.

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Cab sun visor

As with cab roof rims, the primary function of sun visors is not normally perceived as aerodynamic. Nevertheless, potentially the feature can have a significant influence on the airflow around the vehicle, so it is considered here.

External cab sun visors typically have one of two basic designs: a slightly profiled protuberance extending horizontally from just in front of the cab roof; or a rounded piece with a vertical extension over the top of the cab windscreen. The former will increase the aerodynamic drag in nearly all circumstances, although the degree to which this occurs will depend strongly on the details of the installation. The second of these is of much more interest since it effectively constitutes a method of rounding the front roof edge. The discussion below refers to this latter arrangement only.

Relative merits for drag reduction

Benefits	Limitations
• Drag reductions in circumstances where a round roof edge is beneficial.	• Drag increases in circumstances where a sharp roof edge is beneficial.
• Can be used in conjunction with cab roof deflectors or cab roof fairings.	• Probable minor drag increments if the roof edge was already rounded.
• Will decrease drag in the absence of a container if roof edge was sharp.	• Less effective for rigid and drawbar trucks without a deflector/collar.

Additional benefits

The primary purpose of the device is usually to minimise glare while driving.

Purchasing notes

Only really beneficial for cabs with sharp front roof edges.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Rigid	-0.14	200	3.6	0.2	4.3	0.1	2.6	0.2
Articulated	-0.11	200	1.6	0.2	1.9	0.3	1.2	0.4
Drawbar	-0.14	200	1.9	0.2	2.3	0.2	1.4	0.3

Note: Drag reductions relate to values obtainable when cab and container roofs are at same level.

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Cab roof deflector

Essentially a flat or slightly contoured plate of variable angle supported on the cab roof, this is perhaps the most effective single add-on for a vehicle used in conjunction with containers of widely varying heights or a tractor that is used frequently without a trailer.

A well-adjusted deflector can yield a similar overall drag coefficient for the vehicle, irrespective of the relative heights of container and cab roof. As might be expected, the potential drag reductions are greater as the container protrudes more above the cab roof. However, if this type of device is used without a trailer present and is not lowered to its horizontal position, then it will increase the drag of the vehicle significantly.

Relative merits for drag reduction

Benefits

- One of the most effective methods for drag reduction.
- The most adjustable cab roof device - can be used with containers of differing heights and lowered in the absence of a container.
- In the absence of a container, a well-designed, convex-shaped deflector in its lowered position can also slightly reduce the fuel consumption.

Limitations

- Less effective in crosswind environments than roof fairings.
- Incompatible with other types of cab roof fitting.
- Adjustability irrelevant if the same container is always used (e.g. most rigid and drawbar trucks). In this case, a fixed fairing is preferable.
- Perform poorly if concave in side profile.

Additional benefits

- The device provides a natural location for the operator’s name or other advertising.
- Lighter than adjustable fairings for weight-critical applications.

Purchasing notes

- Ensure that the deflector covers the maximum possible portion of the container front edge when viewed from the front. Deflectors that are narrower at the top than the bottom generally prove to be less effective.
- For each mounting location, deflector effectiveness increases significantly with deflector size. Therefore, deflectors should extend as close to the front of the container as is practicable, while avoiding interference with the container when the vehicle is covering rough terrain and cornering (articulated vehicles).
- Avoid deflectors that are concave in side profile. These are difficult to adjust properly and are outperformed by convex profile deflectors.
- The aerodynamic loads acting on the deflector are quite large. Make sure that the fixings are strong and secure.

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Purchasing notes (continued)

- Perhaps the principal advantage that deflectors have over fixed roof fairings (typically in the same price and mass range) is their adjustability. To make the most of this, the adjustment method should:
  - offer a wide range of angles (including one that allows the deflector to lie practically flat on the cab roof if the cab is to be used without a container);
  - allow the blade to be adjusted finely in the angular region of most interest;
  - be rigid and capable of withstanding repeated adjustment;
  - be rapid to use (thereby minimising additional outlay to perform the adjustment).
- The position and alignment of the deflector are critical in determining its performance. If using the same deflector set-up on a large number of identical vehicles, it may be worth optimising the arrangement in wind-tunnel or track tests.

Adjustment/operational details

- Careful adjustment is necessary to realise maximum benefit. The consequences of not paying attention to this are, perhaps, more severe for articulated than for rigid or drawbar trucks. Assessments with half-cab deflectors have demonstrated that maladjustment of deflectors for rigid vehicles can increase the drag of the vehicle by up to 5% relative to the optimum drag. For articulated vehicles, the corresponding figure is over 20%. In each case, the worst effects are a result of adjusting the deflector to be too low.
- The optimum adjustment angle depends on the height, shape and location of the deflector relative to the container roof edge. Consequently, assessment of the best angle requires some degree of 'trial and error'.
- For use in conjunction with sharp-edged containers:
  - To set the deflector to approximately the correct height, a straight edge extended from the trailing portion of the deflector should pass above the front roof edge of the container. The nearer the trailing edge of the deflector extends to the container, the smaller the gap should be between the straight edge and the container face. Thus, if the deflector extends to the front of the container, the trailing edge should be in contact with the container edge.
  - The initial estimate can be refined by examining the dirt film on the container. A darker band may be visible after some use; if no band is visible, the deflector may have been adjusted too high. The darker band approximately marks the region in which the flow re-attaches to the container. The largest drag reductions will be obtained when the air re-attaches at the front roof edge of the cab. Therefore, the deflector should be angled so that the dark band is barely visible at the centre of the container roof edge, and perhaps a little more so at the edges.
- For use in conjunction with containers possessing rounded edges:
  - The recommended adjustment procedure is fundamentally similar to that outlined above for sharp-edged containers. However, arranging for the flow to re-attach at the lower limit of the curved part of the roof edge may prove more beneficial.
- To maximise savings, it is important that roof deflectors are lowered or removed when no container is present. Over a given journey, a raised deflector used on an articulated tractor in isolation will **increase** the proportional fuel consumption by double the amount saved when the tractor is used with a container.

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Adjustment/operational details (continued)

- If the cab is used frequently with similar containers of differing height, a 'common sense' approach will minimise the routine set-up time required once a satisfactory adjustment has been found. Mark the deflector's adjustment setting appropriate to the container (e.g. the hole used for 'peg and hole'). It is perhaps best to do this on the deflector mechanism itself, with a suitable indelible marker, rather than make a separate note. If the markings denote the container heights, then these can be used to produce a good estimate for any new size of container encountered.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Rigid	-0.10	300	2.4	0.4	3.0	0.3	1.7	0.5
Articulated	-0.16	300	2.4	0.3	2.8	0.2	1.7	0.4
Drawbar	-0.09	300	1.2	0.5	1.5	0.4	0.9	0.7

Cab roof fairing

This is a three-dimensional moulding, which may or may not be adjustable, that fits on the cab roof. It constitutes perhaps the single most effective add-on device when used in conjunction with an appropriate container size. The fairing works by presenting the airflow with a smooth transition from the cab roof to the container.

Relative merits for drag reduction

Benefits

- Most effective single type of add-on device if a trailer is always present.
- Adjustable fairings permit maximum savings to be made over a range of container heights.
- Good performance in all wind conditions can be achieved through careful matching of the fairing to the vehicle shape.

Limitations

- Incompatible with other types of roof fitting.
- Even adjustable variants have limited ranges and, as a result, are less suitable for units travelling regularly without a trailer.

Additional benefits

- Provides a natural place for the name of the operator on the front of the truck.
- Possibly the smartest roof fitting.
- A sleeping or storage area can be incorporated into the extra space on top of the cab.

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Purchasing notes

- Fairings with a partial U-shape when viewed from above offer the best overall performance in all wind conditions.
- Rounded edges on the fairing sides are desirable.
- If the volume inside the fairing is not intended for other purposes, then slightly better performance will be achieved if the back is left open.
- Make sure that the fairing matches the height of the container if it does not offer scope for adjustment.
- Before purchase, consider whether a collar is required for rigid and drawbar trucks.
- Unless the fairing is to be used with a collar, make sure it covers the maximum possible proportion of the container front roof edge when viewed from the front. (Fairings for use with collars are typically smaller and mounted further forward; the collar is used to cover the front of the container roof edge.)
- Ideally, roof fairings should be fitted in conjunction with cab side fairings or collars. If the two are not to be fitted together, make sure that a side fairing kit could be added at a later date.
- Adjustable fairings, in particular, have large masses. Ensure that the mounting locations for these are located at suitable structural points. Some older designs were bolted directly into the cab roof. These were capable of causing structural damage over rough terrain.
- Ensure that the underside of the fairing and the fittings insulate the cab against noise; most modern ones do. Older designs of hollow fairings have been known to resonate loudly. This is not just unpleasant for the driver but also increases fatigue.

Adjustment/operational details

- Careful adjustment is required to realise maximum benefit and, if in doubt, it is perhaps preferable for the fairing to be adjusted too high rather than too low. For rigid vehicles, a fairing that is too low by less than 15% of the difference between the heights of the cab and container roof can increase the drag by over 15% relative to the optimum height. A corresponding increase in the fairing height has been found to increase the drag coefficient by about 5%.
- For adjustable fairings, use the same procedure as outlined for deflectors.
- Adjust fairings to minimum height in the absence of a container.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Rigid	-0.20	400 (650)	4.8	0.2 (0.4)	5.9	0.2 (0.3)	3.5	0.3 (0.5)
Articulated	-0.25	400 (650)	3.7	0.2 (0.3)	4.4	0.2 (0.3)	2.7	0.3 (0.5)
Drawbar	-0.17	400 (650)	2.3	0.3 (0.5)	2.8	0.3 (0.5)	1.7	0.5 (0.8)

Notes: Values refer to correctly adjusted fairings. Quantities in brackets refer to adjustable fairings (where the values for these features differ from those for fixed fairings).

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Cab roof fairing and collar

Typically, collars are either fixed pieces mounted on the front of the containers or rearward extensions to a specific fixed roof fairing. As the name implies, these items bridge the gap between the cab and container along both sides and roof.

Relative merits for drag reduction

Benefits

- Effective in all wind conditions.
- Forms the most effective transition between the cab and container when used in conjunction with a suitable cab roof fairing.
- No adjustment required.

Limitations

- Requires cab roof fairing (variants that do not are assessed under 'container front fairing').
- Clearly inappropriate for use in conjunction with other cab side fairings, vortex stabilisers/gap seals or other container front fairings.
- Inappropriate in the unlikely event that the container is to be moved from vehicle to vehicle.

Additional benefits

- Can give improved stability in crosswinds.
- Improved vehicle appearance.

Purchasing notes

- Consider purchasing the collar at the same time as purchasing a cab roof fairing.
- Attachment of collar to deflector is, perhaps, aerodynamically inferior in comparison with attachment to container, but should be less expensive to install.
- The short distance between the cab and container of rigid vehicles usually requires the collar to be at a significant angle relative to the direction of vehicle travel. To ensure that large-scale flow separation does not occur at the front edge of the container, the rear portion of the collar should offer a smooth transition to the container sides. The minimum radius required to achieve this reduces as the collar sides become more aligned with the side and roof of the container. As a guide, however, a radius of 75 mm (3 in.) should be sufficient to ensure good performance, irrespective of the overall alignment of the collar.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Rigid	-0.27	650	6.5	0.3	8.0	0.2	4.7	0.4
Drawbar	-0.23	650	3.2	0.4	3.7	0.4	2.3	0.6

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Cab side fairings

Side fairings, as the name implies, are located on the side of the rear cab edges and are used to bridge the gap downstream to the container. Therefore, the magnitude of the drag reduction that may be achieved by the feature depends greatly on the initial size of the gap.

Relative merits for drag reduction

Benefits

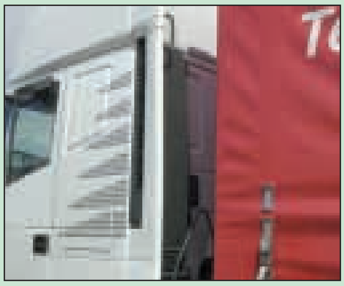
- Side fairings offer an effective means for reducing the drag of trucks that have large gaps between the cab and container.
- Perform a similar task to vortex stabilisers/gap seals. Side fairings are probably more effective if used in conjunction with a cab roof deflector or fairing.

Limitations

- Aerodynamic advantage related mainly to reduced drag in crosswind environments.
- Ideally require cab roof fairings or deflectors to limit airflow in the gap between the cab and container.
- Little merit in employing these in conjunction with a vortex stabiliser/gap seal.
- Savings with container front fairings are not directly additive.

Additional benefits

- Improved stability in crosswinds.
- Smarter vehicle appearance.



Purchasing notes

Side fairings should cover as much of the longitudinal gap between the cab and container as possible.

Adjustment/operational details

- When viewed from the front of the truck the fairings should not extend beyond the width of the container sides, otherwise drag may be increased in calm conditions.
- As with roof fairings, adjust side fairings to minimise frontal area if there is no container present.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Articulated	-0.04	350	0.6	1.2	0.7	1.1	0.4	1.8

Note: Values assume cab roof deflector/fairing already present.

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Tractor side panels

These sections cover the gap between the front and rear sets of tractor wheels. They prevent air that is flowing past the sides of the vehicle from interacting with the cavity between the tractor wheels.

Relative merits for drag reduction

Benefits

- Significant spray suppression if the panel covers a wheel arch.
- Effective in crosswind conditions.
- Reduced drag with and without a trailer or container.
- No adjustment required.

Limitations

- Only reduces drag significantly if the tractor does not already have mechanical components between the wheels.

Additional benefits

- Marginally improved safety for cyclists and pedestrians.
- Improved vehicle appearance.

Purchasing notes

- Ensure that service access to mechanical components is not impeded.
- Vulnerable to damage from stone chips. Consider colour-impregnated rather than painted panels to limit visibility of any damage.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Articulated	-0.04	750	0.6	2.5	0.7	2.5	0.4	4.4

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Low drag mirrors

Standard truck mirrors constitute relatively bluff protuberances at a critical point on the vehicle. Consequently, there is significant scope to improve these items, although, due to their small size, the drag coefficient reduction is limited.

Relative merits for drag reduction

Benefits

- Low drag mirrors offer some advantage in all wind conditions.
- Adjustment for aerodynamic reasons is not required if the mirrors are well rounded.

Limitations

- The drag reduction is small compared to the add-ons already detailed in this Section.

Additional benefits

Smarter appearance than standard mirrors.

Purchasing notes

- The front face of the mirror should be well rounded to have any aerodynamic benefit.
- Mounting arms and brackets also contribute to the overall drag, so there should be as few protruding supports as possible. These supports should be well rounded and, ideally, of elliptic or aerofoil cross-section.
- A small mirror will minimise the frontal area and therefore reduce the drag. Of course, the mirror should not be so small as to compromise rear visibility.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Rigid	-0.01	100	0.2	1.0	0.3	1.0	0.2	1.8
Articulated	-0.01	100	0.1	1.0	0.2	1.2	0.1	2.1
Drawbar	-0.01	100	0.1	2.0	0.2	1.3	0.1	2.3

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Tractor chassis filler panels

A metal plate or grille attached to the upper surface of the tractor chassis behind the cab, this can prevent unwanted airflow through the tractor chassis.

Relative merits for drag reduction

Benefits	Limitations
● Other devices do not duplicate any drag reduction obtained.	● Very limited drag reduction for container trucks, although may be more effective for flatbed and tanker vehicles.

Additional benefits

- Panel can prove useful to improve access to the rear of the cab and front of the container. Make sure that service access to mechanical components beneath is not unduly restricted.
- Improved vehicle appearance.

Purchasing notes

- Any aerodynamic effect exerted by the device is a result of the blockage presented between the gap between the cab and container and the underside of the vehicle.
- Panels have more effect on trucks with large gaps between chassis members behind the cab than on trucks whose chassis is tightly packed with mechanical components.
- Ideally, the filler panel should cover the full width and length of the rear of the tractor unit up to the front of the container.
- In theory, a benefit should result if used in conjunction with cab roof and side fairings, and there is some anecdotal evidence to this effect. However, a rigorous quantification of this has not been documented.
- Smooth panels can prove treacherous in wet conditions. This is usually overcome by a suitable raised pattern and/or holes in the design.
- Any holes in the plate should be small to optimise aerodynamic efficiency.
- Fitting the panel may reduce engine and transmission cooling airflow.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Articulated	0.00	750	0	n/a	0	n/a	0	n/a

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Vortex stabilisers/gap seals

A gap seal is a central projection mounted on the front face of the container, which extends forward almost to the cab and vertically from the base of the container to the height of the cab. A vortex stabiliser is similar, although it typically runs to only approximately three-quarters of the cab height. For articulated vehicles, these items represent an effective alternative to cab side fairings. They are also one of the primary methods for reducing the adverse effect of the tractor-trailer gap on the aerodynamic drag of drawbar vehicles.

Relative merits for drag reduction

Benefits

- Can be used between tractor and trailer of drawbar trucks, and between the cab and container on articulated vehicles.
- Most beneficial on trucks with a large gap between the cab and container.
- Can be used in conjunction with a cab roof fairing or deflector and container fairing (drag reduction effects are not directly additive).
- No adjustment required.

Limitations

- Aerodynamic advantage is restricted mainly to reduced drag in crosswind environments.
- Perform a similar task to cab side fairings, so there is little point in using the two together.

Additional benefits

Improved crosswind stability.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Articulated	-0.04	350	0.6	1.2	0.7	1.1	0.4	1.8
Drawbar	-0.06	350	0.8	0.9	1.0	0.8	0.6	1.3

Chassis/trailer side panels

One of the most popular generic types of add-on device, these cover the gaps adjacent to the underbody on rigid vehicles and adjacent to the underbody on the trailer of articulated vehicles.

Relative merits for drag reduction

Benefits

- Effectiveness increases in cross-wind environments.
- Can also be used on drawbar trailers.
- No adjustment required.

Limitations

- Much smaller drag reduction if vehicle already has equipment located below container (e.g. for loading/unloading).

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Additional benefits

- Improved crosswind stability.
- Shrouding of non-steering wheels reduces spray and, in turn, reduces soiling of the vehicle sides.
- Improved safety for pedestrians and cyclists.
- Possible location for side lockers set into the trailer skirts.
- Improved vehicle appearance.

Purchasing notes

- Vulnerable to damage from stone chips and side loading. Consider colour-impregnated rather than painted panels to limit visibility of any damage.
- In principle, panels that taper in at the rear should help to reduce drag further.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Rigid	-0.04	750	1.0	2.1	1.2	2.0	0.7	3.7
Articulated	-0.03	950	0.4	3.8	0.5	4.6	0.3	9.1
Drawbar	-0.05	1,700	0.7	4.9	0.8	5.5	0.5	11.8

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Container front fairing

Mouldings around the edge on the front of the container and/or drawbar trailer encourage the airflow to remain attached at the front of the container roof and sides.

Relative merits for drag reduction

Benefits

- Can be used between tractor and trailer of drawbar trucks as well as between the cab and container on the tractor.
- Most effective single add-on device if the trailer is present only half of the time.
- Effective in all wind conditions.
- Can be used in conjunction with devices fitted to the cab.
- No adjustment required.
- Fitting a front fairing allows the height of any roof fairing or deflector to be reduced in order to improve performance in crosswinds.

Limitations

- Lower level of drag reduction if used in conjunction with a deflector or fairing.
- Lower level of drag reduction on drawbar trailers if trailer roof height is reduced.

Purchasing notes

- Typically, fairings are either located around the perimeter of the container front or they cover the entire container front above the level of the cab. It is the region around the edges that primarily offers the aerodynamic drag reduction and, therefore, in general, such fairings may prove more cost-effective.
- Consequently, containers with radiussed edges built in will offer significantly improved levels of aerodynamic performance relative to basic sharp-edged designs. If the container already has radiussed edges and is to be used in conjunction with an extensive cab roof fairing and collar, there are minimal additional fuel savings available through use of a moulding that projects forward of the container (unless this is the only means available to reduce the gap between cab and container).
- Some fairings take the form of squat pyramids located in the middle of the container above the level of the cab. These are almost completely ineffective.
- The relative effectiveness of the various shapes available is perhaps not intuitively obvious. Therefore, it is particularly valuable to check any savings figures quoted by the manufacturer, prior to purchase.

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In conjunction with other devices

- The performance of container fairings is exceptionally robust, although their relative effectiveness depends on the shape of the cab and any devices fitted to the cab roof and sides.
- Container fairings can be used in conjunction with cab roof deflectors and side fairings. However, the effect of the container fairing will be minimal if the cab fairings cover the entire front of the container when viewed from the front, or if the cab fairings are very close to the container. As a result, the savings from the devices are not directly additive.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Rigid	-0.15	350	3.6	0.3	4.4	0.2	2.6	0.4
Articulated	-0.12	350	1.8	0.4	2.1	0.3	1.3	0.6
Drawbar (tractor)	-0.12	350	1.6	0.4	1.9	0.4	1.2	0.6
Drawbar (trailer)	-0.05	350	0.7	1.0	0.8	0.9	0.5	1.6

Container/trailer roof tapering

Tapering the rear roof of the container or trailer offers an effective way of reducing the drag caused by the rear of the vehicle and involves the loss of perhaps the least useful region of the internal container space.

Relative merits for drag reduction

Benefits

- Some advantages in all wind conditions.
- The technique can also be applied to drawbar trailers.
- No adjustment required.

Limitations

- Impractical to retrofit.

Purchasing notes

- A drip collection trough is recommended to prevent excessive amounts of water running down the rear of the container.
- Longer tapers with shallow angles are better than short steep ones. In particular, the angle of the bevelled piece should not exceed 12° from the horizontal.
- The taper should be as deep as is permitted by internal load space and loading considerations.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Rigid	-0.02	250	0.5	1.7	0.6	1.3	0.3	2.3
Articulated	-0.02	250	0.3	1.7	0.4	1.6	0.2	2.7
Drawbar (tractor)	-0.01	250	0.1	5.0	0.2	3.8	0.1	7.2
Drawbar (trailer)	-0.02	250	0.3	1.7	0.3	1.7	0.2	3.0

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Trailer roof height reduction

Significant drag reductions are possible on drawbar vehicles by a modest reduction of trailer height below that of the tractor. Inevitably, there is a minor penalty associated with the volume of cargo that the vehicle is capable of transporting, and the apparent 'mismatch' between tractor and trailer heights may also mean that the vehicle does not appear as smart as one with matching tractor and trailer roofs.

Relative merits for drag reduction

Benefits	Limitations
• Significant drag coefficient reductions, even in crosswind environments. • No adjustment required.	• Not applicable for retrofit. • No flexibility for use with tractors of different height. • Will reduce level of additional savings achievable using other features in the gap between tractor and trailer. • Little benefit if the cab roof has sharp edges, as the airflow over the top of the vehicle is already disturbed in advance of the trailer.

Purchasing notes

- Further drag reductions are possible if a slightly narrower trailer is used, although this approach will have a more substantial adverse effect on the cargo capacity.
- A height reduction of 10% of the tractor height is probably about optimal.

Truck type	Change in Cd_{ave}	Estimated cost (£)	A		B		C	
			Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)	Fuel saving (%)	Payback time (years)
Drawbar	-0.06	0	0.8	n/a	1.0	n/a	0.6	n/a

3.3 Aerodynamic Implications of Other Features

Clearly, there are many other features that are commonly attached to vehicles to satisfy requirements that are not aerodynamic. Nevertheless, these features can have significant effects on the aerodynamic performance of the vehicle. Therefore, prior to fitting such features it is important that you balance the need to have them, with the detrimental effect on fuel economy. For indicative purposes, changes in fuel consumption are predicted for a vehicle in the 'Case A' situation presented in Section 3.2.

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Additional lights/horns

Generally, these items only increase vehicle drag. The position in which lights should be cited to limit this adverse effect as far as possible varies according to the aerodynamic treatment of the cab. For rigid or drawbar vehicles without fairings or deflectors, and articulated vehicles with sharp front roof edges, it may be possible to locate lights and horns at some distance back from the front edge if a high vantage point is necessary. Alternatively, positioning the lights below the level of the windscreen may be preferable. Similar guidelines apply to locations at which ornamental detritus will have the minimum adverse effect.

Truck type	Change in Cd_{ave}	Additional fuel use (%)
Rigid	0.005	0.1
Articulated	0.005	0.1
Drawbar	0.005	0.1

Note: Estimates are based on a single, typical light located on the rounded roof edge of a cab with a deflector or fairing.

Rear full-width mud/spray guard

This feature increases drag if used in isolation. Moreover, although the level of spray exhausted from the rear of the vehicle is reduced, the increased pressure generated on the front face of the flap encourages spray to be exhausted from the side of the vehicle if the feature is used in isolation. Consequently, the safety of adjacent motorists may be adversely affected.

Truck type	Change in Cd_{ave}	Additional fuel use (%)
Rigid	0.03	0.7
Articulated	0.04	0.6
Drawbar	0.03	0.4

Note: Estimates are based on vehicles without air dams.

Refrigeration unit

If no other aerodynamic features are applied, this feature will actually confer a minor drag decrease when used in conjunction with articulated vehicles. The effect on rigid and drawbar vehicles is unclear.

Truck type	Change in Cd_{ave}	Additional fuel use (%)
Rigid	-0.03	-0.7
Articulated	-0.03	-0.4
Drawbar	-0.03	-0.4

3.4 Summary Table of Aerodynamic Drag and Fuel Savings

Table 3 summarises the aerodynamic performance of the add-on devices. The fuel savings predicted for the circumstances corresponding to 'Case A' (described in Section 3.2) are also presented, together with the associated payback times.

Feature	Performance			Financial			Notes
	Change in Cd_{ave}	Estimated fuel savings (Case A) (%)	Mass (kg)	Typical cost (£)	Estimated value of savings per 160,000 km (100,000 miles) (£)	Estimated payback time (years)	
Cab roof fairing and collar							Most effective add-on. Ideally, requires the same size of container to be in position permanently.
Rigid	-0.27	6.5	35	650	2,300	0.3	
Drawbar	-0.23	3.2	35	650	1,600	0.4	
Cab roof fairing							Numbers in brackets refer to adjustable fairings where such values differ.
Rigid	-0.20	4.8	20 (70)	400 (650)	1,700	0.2 (0.4)	
Articulated	-0.25	3.7	20 (70)	400 (650)	1,900	0.2 (0.3)	
Drawbar	-0.17	2.3	20 (70)	400 (650)	1,200	0.3 (0.5)	
Cab sun visor							Effective only over a very limited set of conditions.
Rigid	-0.14	3.6	5	200	1,270	0.2	
Articulated	-0.11	1.6	5	200	836	0.2	
Drawbar	-0.14	1.9	5	200	985	0.2	
Cab roof deflector							The most adjustable add-on. Especially useful for tractors used frequently without trailers, or flatbeds that must occasionally accommodate tall loads.
Rigid	-0.10	2.4	20	300	850	0.4	
Articulated	-0.16	2.4	20	300	1,200	0.3	
Drawbar	-0.09	1.2	20	300	650	0.5	
Container front fairing							Effective means of reducing drag with no scope for maladjustment. Some care is required during selection.
Rigid	-0.15	3.6	15	350	1,300	0.3	
Articulated	-0.12	1.8	15	350	900	0.4	
Drawbar (tractor)	-0.12	1.6	15	350	850	0.4	
Drawbar (trailer)	-0.05	0.7	15	350	350	1.0	
Cab roof rim							Effective only over a very limited set of conditions. Incompatible with other cab-roof mounted drag reduction features.
Rigid	-0.04	1.0	5	100	364	0.3	
Articulated	-0.10	1.5	5	100	760	0.1	
Drawbar	-0.04	0.5	5	100	282	0.4	
Trailer roof height reduction							
Drawbar (trailer)	-0.06	0.8	0	0	400	n/a	
Chassis/trailer side panels							Expenditure may be questionable for drag reduction alone but feature also offers significant spray reduction benefits.
Rigid	-0.04	1.0	130	750	350	2.1	
Articulated	-0.03	0.4	130	950	250	3.8	
Drawbar	-0.05	0.7	250	1,700	350	4.9	
Cab side fairings							A significant improvement when used in conjunction with a roof fairing or deflector.
Articulated	-0.04	0.6	20	350	300	1.2	

Table 3 Summary of drag reductions and fuel savings for add-on aerodynamic features

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Feature	Performance			Financial			Notes
	Change in Cd_{ave}	Estimated fuel savings (Case A) (%)	Mass (kg)	Typical cost (£)	Estimated value of savings per 160,000 km (100,000 miles) (£)	Estimated payback time (years)	
Vortex stabilisers/gap seals							Similar function to cab side fairings for articulated vehicles.
Articulated	-0.04	0.6	10	350	300	1.2	
Drawbar trailer	-0.06	0.8	10	350	400	0.9	
Air dam							Reasonably effective means of reducing drag, with no scope for maladjustment. Already present on most modern vehicles.
Rigid	-0.03	0.7	10	250	250	1.0	
Articulated	-0.02	0.3	10	250	150	1.7	
Drawbar	-0.02	0.3	10	250	150	1.7	
Tractor side panels							May not be required for drag reductions on some tractors.
Articulated	-0.04	0.6	50	750	300	2.5	
Cab side edge turning vanes							Values are for vehicles with inadequate edge radiussing adjacent to windscreen. This edge is radiussed sufficiently for most modern vehicles.
Rigid	-0.02	0.5	2	100	150	0.7	
Articulated	-0.02	0.3	2	100	150	0.7	
Drawbar	-0.02	0.3	2	100	150	0.7	
Container trailer roof tapering							Unsuitable for retrofitting.
Rigid	-0.02	0.5	1	250	150	1.7	
Articulated	-0.02	0.3	1	250	150	1.7	
Drawbar (tractor)	-0.01	0.1	1	250	50	5.0	
Drawbar (trailer)	-0.02	0.3	1	250	150	1.7	
Low drag mirrors							Minor drag reductions.
Rigid	-0.01	0.2	1	100	100	1.0	
Articulated	-0.01	0.1	1	100	100	1.0	
Drawbar	-0.01	0.1	1	100	50	2.0	
Tractor chassis filler panels							Possible benefits if used in conjunction with cab roof and side fairings.
Articulated	0.00	0	15	750	0	n/a	

Table 3 Summary of drag reductions and fuel savings for add-on aerodynamic features (continued)

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4 MAXIMISING AERODYNAMIC SAVINGS

To maximise the potential savings offered by aerodynamic improvements, it is important that you appreciate the factors that indirectly alter the fuel consumption with any given aerodynamic package. Some of the most significant factors and their influence on fuel economy are discussed in this Section.

4.1 Position of the Load

For flatbed vehicles, the load also forms part of the external vehicle shape. Therefore, suitable location and orientation of the load can realise fuel savings. Some guidelines are presented below.

- Arrange the load so that it protrudes as little as possible beyond the perimeter of the cab when viewed from the front. This minimises the frontal area of the vehicle and typically improves the drag coefficient (see Section 2.1).
- Locate the load as close as possible to the back face of the cab, without exceeding legal axle weights. This has the same effect as reducing the gap on articulated vehicles.
- If the load does not have the same cross-sectional area along the vehicle length, position the larger end nearest to the cab.

For vehicles with a flat bed instead of a closed container, whenever possible make sure that large loads are placed nearest to the cab. The principle behind this is the same as for minimising the gap between a cab and container and can have a significant drag reduction benefit (see Fig 9).

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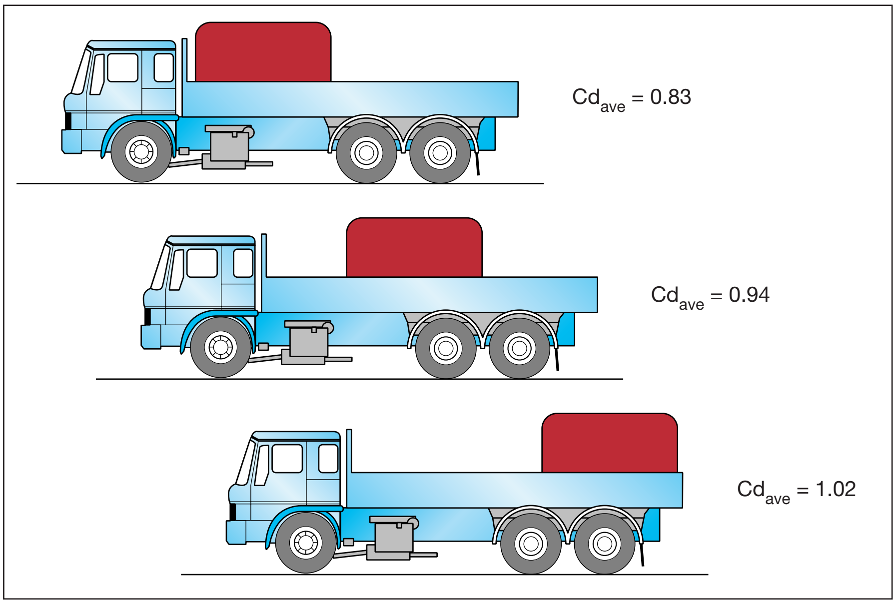

Fig 9 Effect of load location on the drag coefficient of a flatbed vehicle

4.2 Gear Ratio Changes

Aerodynamic drag reduction minimises the power that a vehicle must produce to move at a constant speed. Consequently, after aerodynamic improvement, further fuel savings can be obtained by a corresponding change to the vehicle gearing. In practice, it is usually sufficient to change only the gears that are used for constant high speed travel (e.g. the gear that the vehicle will use as the speed limiter cuts in).

The procedure outlined in Fig 10 presents a method for respecification of the gearing. The engine manufacturer should be able to provide you with the information needed to permit specification of the gearing reduction.

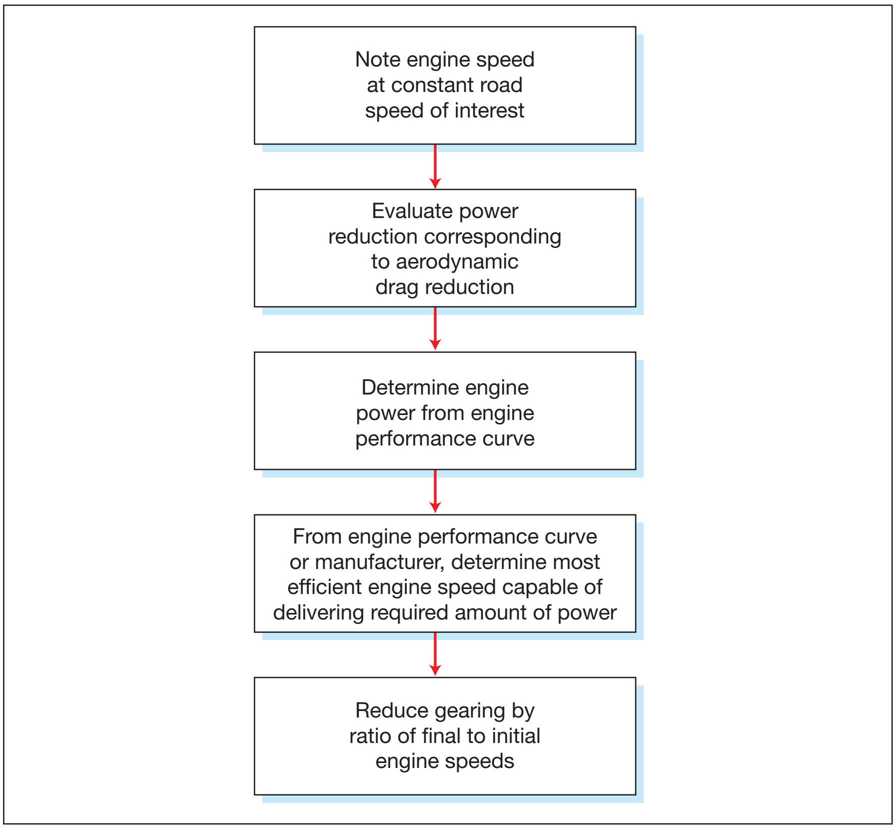

Fig 10 Flow chart describing steps required to optimise gearing

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5

EVALUATION OF MANUFACTURERS' CLAIMS

The previous Sections have presented guidelines to help you assess a number of aerodynamic features. It may also be necessary to select a good design of the feature under consideration. For some features, such as side panels and roof rims, there are limited differences between the aerodynamic effects of different versions of the same basic feature, and selection of the particular design can be guided confidently by other criteria. For other features, such as cab roof deflectors and fairings, there can be significant differences between the effectiveness of different designs. Although the preceding Sections have given you some guidance on general features to look out for in each case, it may, nevertheless, be necessary to consider the manufacturer's claims for each device.

Many manufacturers of aerodynamic add-ons use predicted fuel savings figures in their marketing material - but these should be interpreted with caution. When investigating potential aerodynamic modifications you should enquire about the origins of any quoted fuel savings or drag reduction figures. Such claims are frequently supported by anecdotal evidence only and it is recommended that they are treated with some scepticism. To prove credible, the figure quoted should have been arrived at through a systematic test procedure.

5.1 Available Test Procedures

As already emphasised, the fuel savings achieved by a fleet are highly dependent on operational values as well as the nature of the add-on features. There is no single universally applicable and approved method for evaluating fuel saving values. A variety of techniques can be used but these can deliver substantially different results. Knowing the limitations of the most common techniques will enable you to evaluate the reliability of the quoted results properly.

Table 4 outlines the available methods, together with some of their merits and limitations. You should also consider the following points:

- The vehicle on which the add-on device is mounted should clearly resemble those on which the devices are to be mounted in your fleet.

- If performed with inadequate attention to detail, each of the methods offers substantial scope to predict unrepresentative values. Whatever their development strategy, the manufacturers should be able to describe and support their methodology, ideally with reference to established test procedures.

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TIPS: SOME COMMON PITFALLS

The relative merits of the testing methods are detailed in Table 4. However, the history (or apparent history) of excessive claims made in the industry makes highlighting some of the most common areas for misunderstanding worthwhile.

Wind-tunnel and coast-down testing

Generally, these methods will give reliable predictions of the aerodynamic drag reductions available and are, therefore, valuable for assessing the relative performance of different features. (However, ensure that wind-averaged drag coefficient reductions are quoted). The difficulty usually arises when predicting fuel savings from these values. Typically, such predictions are performed using computer simulations, which do not necessarily take the driver's response properly into account. Look for correlation of the predictions with in-service testing and ensure that the operation on which the predictions are based is similar to yours.

Track testing

The fuel savings predicted here are normally based almost exclusively on a vehicle that is cruising at a high speed over a level surface. This will result in over-prediction of the savings available (unless, of course, this operation reflects that of your fleet).

Road testing

Road testing is frequently performed using trained drivers who are able to obtain increased aerodynamically-derived fuel savings through more disciplined use of the throttle. Thus, the savings presented may again prove optimistic.

Method	Description	Predictions	Advantages	Restrictions	Look for
Wind-tunnel testing	Wind is blown past either the vehicle or a model of the vehicle. The drag force on the model is measured.	Drag coefficient reduction	• Output dependent on feature and vehicle shape under test only. • Some development work to improve the aerodynamic performance will normally have been undertaken. • Direct comparison of relative effectiveness possible. • Although fuel savings are not predicted directly, they can be estimated (from the spreadsheet) for any supplied service route.	• Fuel savings are not predicted directly.	• Wind-averaged drag coefficients should be obtained using a known standard (e.g. SAE J1252). • The scale of the model used for the wind tunnel tests. Ideally, the scale should not be smaller than 1/10th for realistic predictions.
Coast-down testing	The speed profile of a coasting vehicle slowing down under the influence of aerodynamic drag and rolling resistance is used to obtain the aerodynamic drag.	Drag coefficient reduction	• As above, except that the number of tests required to obtain values render development work unlikely.	• As above	

Table 4 Summary of assessment methods for aerodynamic features

Method	Description	Predictions	Advantages	Restrictions	Look for
Track testing	Comparison of fuel consumption of vehicle(s) lapping a test circuit normally at a constant speed, both with and without the feature.	Fuel savings	• Fuel savings are predicted directly. • If testing is performed at the same constant speed, direct comparison of values from different manufacturers is feasible.	• Fuel savings dependent on test conditions, in addition to feature and vehicle shape. • Fuel savings usually very optimistic relative to in-service predictions, as the situation normally corresponds to the one in which aerodynamic drag is most significant.	• Ensure that a description of the vehicle type and speed used is provided.
Road testing	Vehicles both with and without the feature travel on an identical representative test route.	Fuel savings	• Fuel savings are predicted directly. • Fuel savings can be appropriate to an in-service route.	• Fuel savings dependent on utilisation in addition to feature and vehicle shape. • Comparison of results of separate tests performed under different conditions or on different routes may be inaccurate.	• Ensure that a description of the vehicle type, speed and test route is provided. • Standardised test procedure (e.g. SAE J1264).
In-service testing	Some trucks in a fleet using the same general route are fitted with the feature while others are not. The relative fuel consumptions of the two groups are monitored over a long period.	Fuel savings	• The most accurate prediction of fuel savings if the trucks and their operation are similar to those in your fleet.	• Fuel savings dependent on utilisation in addition to feature and vehicle shape. • Comparison of results of separate tests performed under different conditions or on different routes may be inaccurate.	• Ensure that a description of the speed and test route is provided. • Standardised test procedure (e.g. SAE J1264).

Table 4 Summary of assessment methods for aerodynamic features (Continued)

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GLOSSARY OF AERODYNAMIC TERMS

Attached flow	The air follows the contours of the shape around which it is flowing.
Boundary layer	The airflow immediately adjacent to a body must be static relative to that body, while the airflow further away is clearly moving relative to the body. Therefore, there is a region over which the speed of the airflow relative to the body varies dramatically. This region is known as the boundary layer. In practice, the low viscosity of air means that this is typically quite thin (of the order of several centimetres).
Drag	The retarding force exerted on the moving vehicle by the air around it. This is often referred to as air resistance.
Drag coefficient	This directly relates the vehicle shape to the air resistance experienced. The air resistance is also proportional to the frontal area of the vehicle and the wind pressure (see below). For vehicles of similar size, this allows direct comparison of the air resistance experienced in identical conditions. The drag coefficient is specific to the speed of any crosswind relative to the vehicle (see wind-averaged drag coefficient).
Dynamic pressure	See wind pressure.
Form drag	As a travelling vehicle pushes its way through the air, it experiences high pressure at the front and low pressure at the rear. These both act in the same direction to resist the motion of the vehicle, and so contribute to the drag.
Pressure drag	See form drag.
Re-attachment point	The re-attachment point is the location where the airflow, having previously separated, returns to the surface and subsequently follows the shape of the body.
Separated flow	The airflow deviates from the contours of the shape around which it is flowing (opposite of attached flow).
Separation point/line	A point (or, for the full three-dimensional flow, a line) on a body at which the airflow ceases to follow the shape of the body.
Skin friction drag	Air has a very low viscosity. Nevertheless, as the vehicle passes through the air, this viscosity creates a shear force along the surface of the vehicle, which has the same direction as the air relative to the vehicle surface. This contributes a small amount to the overall drag.
Streamlining	The process by which a shape is modified such that the adjacent airflow follows the revised shape.

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Wind-averaged drag coefficient	The drag coefficient of a given vehicle will change depending on the strength of any crosswind. Consequently, it is usual to ascribe an average value based on a statistical analysis of the winds experienced in the UK and the directions of UK motorways.
Wind pressure	A measure of the amount of kinetic energy present in a cubic metre of moving air due to its motion relative to the vehicle. This depends on both the air density and, more significantly, the square of the air speed relative to the truck. Doubling the speed consequently quadruples the wind pressure (and the drag force).
Wind tunnel	To measure the forces on the vehicle and visualise the flow around the vehicle, it is generally more convenient to have the air blown past the vehicle rather than have the vehicle move through the air. The wind tunnel, as its name implies, is a large passage in which the vehicle (or a model of the vehicle) is located while the air is blown past it.

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A

AERODYNAMICS

This Section extends the information on aerodynamics given in Section 2, to both incorporate the influence of atmospheric wind and describe the operation of the features discussed in Section 3.

A.1 Airflow Around a Truck in Conditions of Atmospheric Wind

The drag coefficient described in the Glossary refers to ideal conditions in which the air is still. In these circumstances, the velocity of the air relative to the vehicle is identical in magnitude (although opposite in direction) to the velocity of the vehicle relative to the ground.

In practical situations, some degree of atmospheric wind will be encountered frequently. This wind will alter both the speed and direction of the airflow relative to the vehicle (see Fig 11).

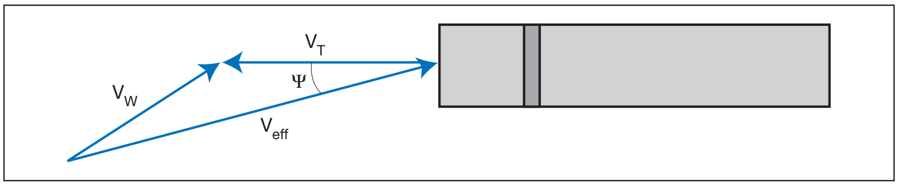

Fig 11 Effective wind speed and yaw angle of airflow experienced by truck

The speed of the truck, V_T, combined with the local windspeed, V_W, gives rise to the effective wind speed, V_{eff}. The **effective yaw angle,** Ψ, is the direction of the wind as perceived at the vehicle. Therefore, the range of effective air speeds and directions encountered by the truck depends on the speed and direction of the wind relative to those of the truck. This variation of effective wind speed and direction is clearly capable of altering the basic flow pattern around the vehicle.

In Fig 12, it is evident that separation on the windward side of the vehicle is suppressed by the action of wind, while on the leeward side the separated flow region is enhanced. This change in flow pattern clearly alters the aerodynamic drag and the drag coefficient of the vehicle. Moreover, it is apparent that crosswind is capable of altering the relative effectiveness of any add-on features for drag reduction. Typically, add-on features located on the front of the vehicle prove more effective in the absence of crosswind (e.g. air dams), while those located on the side of the vehicle become more effective in crosswind conditions.

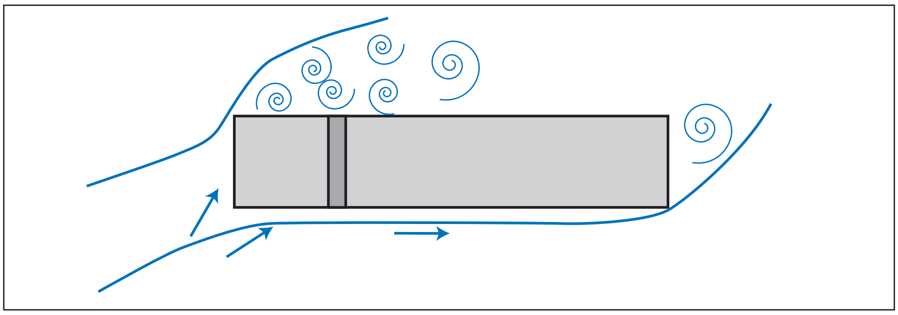

Fig 12 Flow pattern around articulated vehicle

For commercial vehicles, the overall effect of atmospheric wind is typically to increase aerodynamic drag, even though at some points there may be a tailwind. In addition, the crosswind also influences the stability of the vehicle. The three main generic vehicle types react in different ways to sidewinds, so methods of aerodynamic improvement must vary accordingly. A modification that gives an improvement in stability for a rigid vehicle will not necessarily have the same effect for articulated or drawbar models. Additionally, some aerodynamic features that reduce the vehicle drag also reduce the vehicle's stability in crosswind conditions. A compromise is usually necessary in these circumstances.

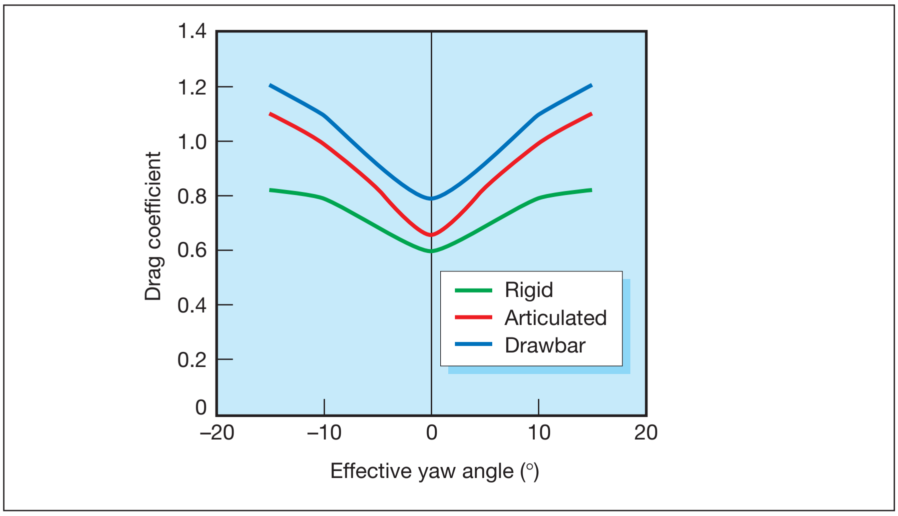

Fig 13 Sample variations of drag coefficient with effective yaw angle

The different airflow around the vehicle, which is a result of this change in the speed and direction of the wind relative to the vehicle, alters the aerodynamic drag. Fig 13 presents some sample curves to show how the drag coefficient varies for some typical vehicle types.

This leads to the definition of a **'wind-averaged' drag** and an associated **'wind-averaged' drag coefficient.** Confusingly, there does not seem to be a universal notation for the wind-averaged drag coefficient, and sometimes the term 'drag coefficient' is used loosely to describe it. Throughout this Guide, Cd_{ave} denotes the wind-averaged drag coefficient. These quantities are defined in a similar manner to the drag above.

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Wind-averaged drag = Cd_{ave} x Frontal area x Wind pressure

The wind pressure in this expression is still based on the vehicle speed relative to the ground, rather than the overall effective wind speed incident on the vehicle.

The wind-averaged drag represents the aerodynamic drag force on the vehicle, incorporating the effects of atmospheric wind averaged over time. It assumes that the vehicle speed and direction are unchanged over the time interval. Therefore, the wind-averaged drag incorporates the mean effect of the relative frequencies of the wind strengths and directions that may be encountered by the vehicle. Consequently, the wind-averaged drag coefficient enables an improved estimate to be made of the aerodynamic drag that is experienced by the vehicle in service. The approach proves particularly valuable for assessing the overall effectiveness of add-on devices that offer a substantial drag reduction in crosswind environments only (e.g. side panels). As a result, it is recommended that comparisons of the aerodynamic drag reduction are undertaken using wind-averaged drag coefficients. This approach has been used throughout this Guide, unless stated otherwise.

Careful consideration of the above suggests that the wind-averaged drag coefficient is specific to:

- the vehicle speed;
- the local meteorology;
- the vehicle orientation (wind does not normally occur with equal frequency from each direction).

In principle, these restrictions limit the range of applicability of wind-averaged drag coefficients. In practice, the use of a wind-averaged drag coefficient, irrespective of the constraints above, nevertheless offers an improvement in the accuracy of the predicted aerodynamic drag. A single wind-averaging procedure also facilitates comparison of drag coefficient reductions supplied by producers of add-on devices.

A.2 Operation of Fuel-saving Devices

The basic causes of aerodynamic drag have been presented in Section 2 and above, together with the overall aims of streamlining. In this Section, the methods by which some of the most common drag-reduction devices operate are presented in greater detail.

Relative height of cab and container, and the effect of front edge rounding

Fig 14 illustrates the following points using the flow patterns for different combinations of cab/container roof height and sharp/rounded roof edges, as applied to articulated vehicles:

- The optimum relative height of the cab and container roof depends on the treatment of the roof edge. Roof edges with rounded radii encourage the flow to remain attached over the cab roof whilst **sharp** cab roof edges ensure that the flow will **separate**. Rounding the front edges of the cab will, therefore, reduce the drag relating to the cab element.
- In general, maintaining attached flow offers the lowest drag, so a rounded roof edge might be expected to provide the best performance, irrespective of the container height. However, if the container height exceeds the cab height and the airflow is made to remain attached across the roof of the cab, it then impinges on the front of the container. This results in a region of high pressure that increases the drag of the container component and, therefore, increases the overall drag of the vehicle.
- **In the absence of a cab roof deflector or fairing,** a sharp roof edge offers the best solution if the container roof exceeds the cab roof level significantly; otherwise, a rounded edge is preferable.

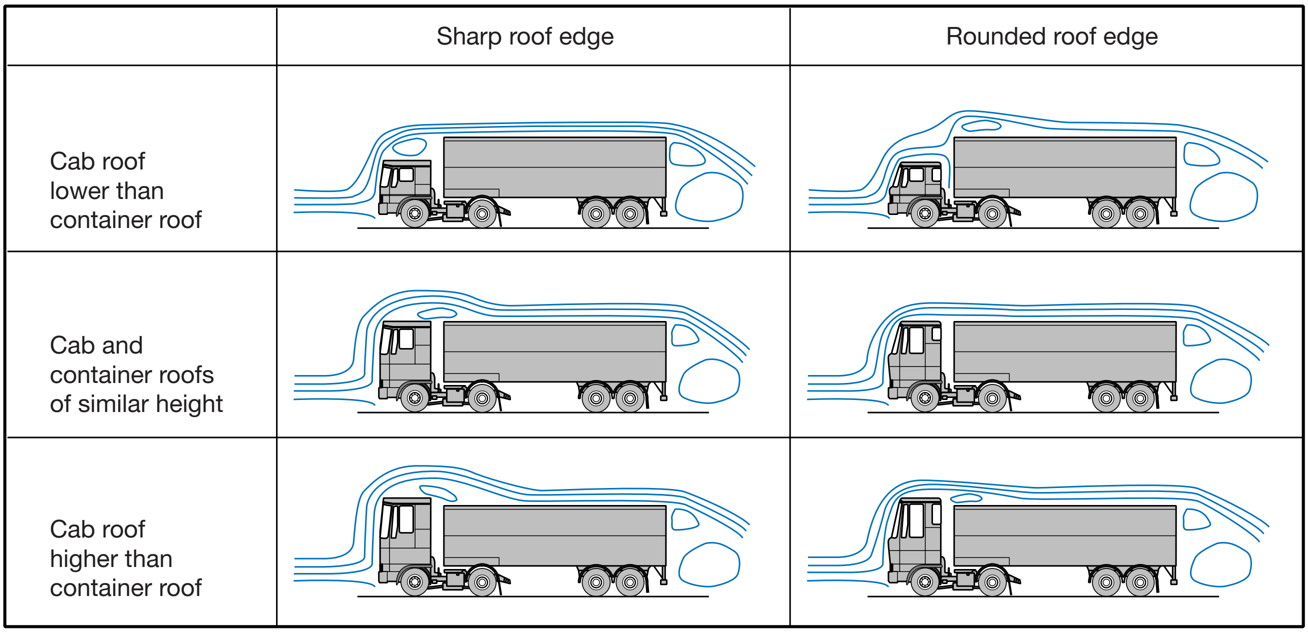

Fig 14 Schematic flow patterns around articulated vehicles with differing cab and container heights, in conjunction with both sharp and rounded cab roof edges

Therefore, it follows that the cab and container cannot be treated separately and that matching their aerodynamic characteristics is crucial for obtaining the largest drag reduction and, therefore, fuel savings.

These points explain the behaviour of the overall drag coefficient for articulated vehicles without fairings or deflectors, as shown in Fig 15 below.

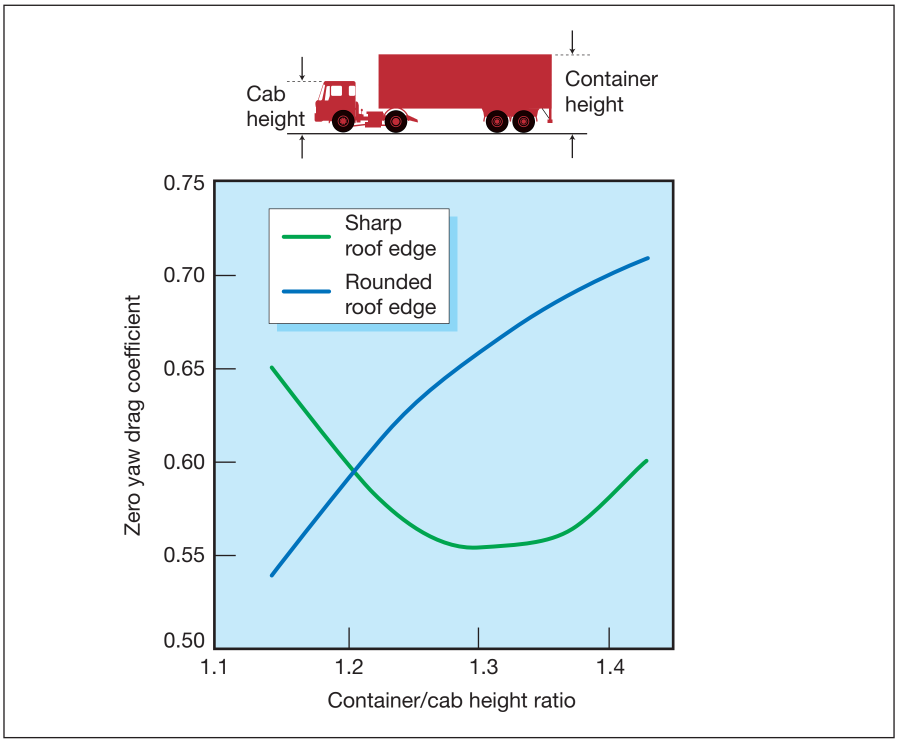

Fig 15 Effect of cab/container height ratio on drag coefficient for different front edge treatments

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Rigid and drawbar vehicles do not possess such a sizeable gap between cab and container, so the airflow cannot be diverted downwards and a separation usually results on the top of the cab roof, irrespective of the front roof edge treatment. Therefore, the problem is not as marked for such vehicles, although similar trends can be expected.

Sun visors with rounded outer faces act as bolt-on edge rounding and suppress separation over the cab roof. Conversely, roof rims act to sharpen the front edge.

As highlighted above, the step between the cab and container roof levels can have a large influence on the drag coefficient. Most frequently, the container is significantly taller than the cab. In this instance, neither of the edge treatments alone is optimal; a sharp roof edge guarantees a region of separated flow above the cab roof while a rounded edge ensures one above the container (as illustrated in Fig 14). The most effective drag reduction devices are typically associated with an improvement in this area; these are considered below.

Tractor-trailer gap

As the separation between articulated tractor and trailer is increased, air is turned downwards into the gap and so the pressure on the rear face of the cab reduces, while that on the corresponding region of the front face of the container increases. Both of these changes in pressure act to increase the total drag of the vehicle.

Fig 16 presents some typical data for the effect of tractor-trailer gap on the drag coefficient in the absence of any crosswind. In a crosswind, this drag increase becomes more marked, as might be expected from the yaw flow diagram in Section A.1.

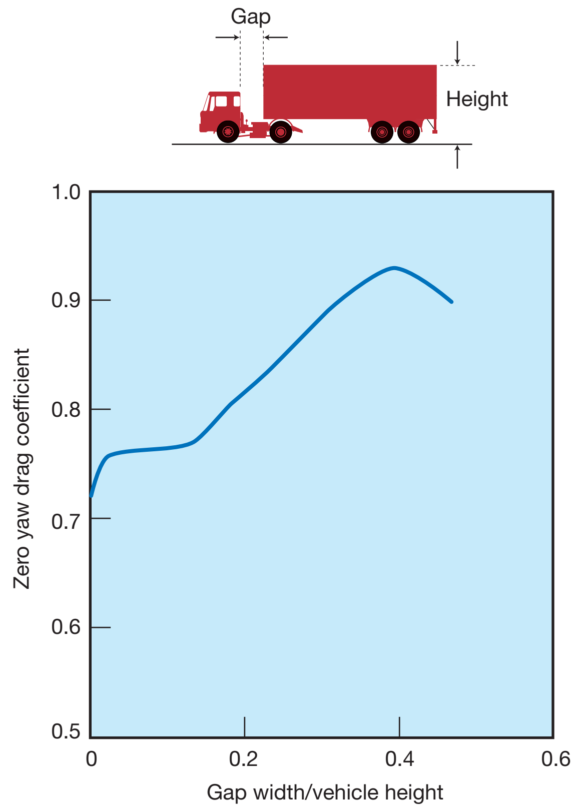

Fig 16 Sample variation of drag coefficient with tractor-trailer gap width for an articulated vehicle

The significant decrease in the drag coefficient with a decrease in gap width is one of the primary reasons why refrigeration units located on the container front offer a drag reduction.

Information presenting the effect of distance between the tractor and trailer of drawbar vehicles is rather more limited. Fig 17 presents sample results for the effect of gap width on a particular (aerodynamically optimised) tractor-trailer combination.

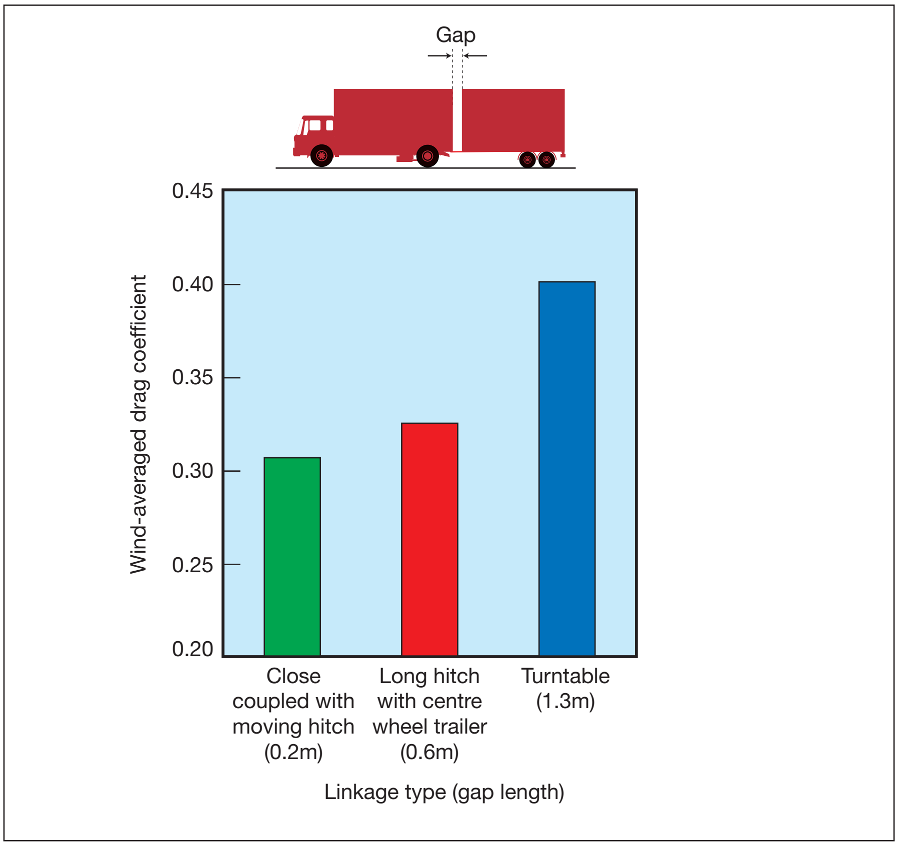

Fig 17 Sample variation of drag coefficient with tractor-trailer gap width for a drawbar vehicle

Cab roof deflectors/fairings

The principal purpose of these items is to ensure a smooth transition between the front roof edges of the cab and container. In the absence of crosswind they can eliminate separation both on the top of the cab and on the top of the container. To offer a smooth transition, the roof edge should be rounded.

Cab roof deflectors also minimise the air flowing between cab and container, which is most relevant for articulated vehicles.

Collar system

A good fairing and collar system excludes airflow from the gap between the cab and container. This eliminates any significant drag contribution caused by a pressure differential between the rear of the cab and the front of the container, and offers improved performance in a crosswind environment. Moreover, the smooth transition between the deflector and cab sides and the perimeter of the container front eliminates separation.

Air dam

Air dams divert air around the sides and roof of the truck, thereby reducing the contribution of the vehicle underbody to the drag. However, the additional airflow around the upper surfaces of the vehicle will exacerbate the drag contribution from these regions.

For articulated container vehicles, there is some circumstantial evidence to suggest that the low-pressure region behind the air dam can increase the amount of air drawn into the gap between cab and container. This will have an adverse effect on the vehicle drag. Therefore, better savings may be obtained if the air dam is used in conjunction with a roof deflector or fairing, side fairings and a chassis filler panel.

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Cab side fairings and vortex stabilisers/gap seals

Flow through the gap between tractor and trailer is blocked by these elements. Thus, the effect of crosswind on the contribution to the drag coefficient resulting from the gap between tractor and trailer is reduced.

Side panels

Side panels limit the interaction of the airflow along the vehicle side with the vehicle chassis, thereby reducing underbody drag.

Tractor chassis filler panels

The filler panel prevents the low-pressure region beneath the tractor chassis from increasing the amount of air drawn into the gap between cab and container. It thereby limits the pressure differential between the rear of the cab and the front of the container, which reduces drag. In practice, however, this means that air passing downwards into this gap must be exhausted from the sides of the gap. Therefore, separation at the front sides of the container is promoted and this causes a drag increase. Clearly, other effects (e.g. relative heights of cab and container, the presence of a cab roof fairing, radiussing on the container front edges) influence the relative magnitudes of the two effects outlined above and, consequently, whether an overall improvement is obtained.

Cab side vanes

The majority of the air passes around the exterior of the vanes. Consequently, the local radius of the edge of the vehicle is, effectively, equal to the outer radius of the vanes. Evidence suggests that any drag reduction obtained derives principally from the increase in the effective radius of the cab edges to a level that is sufficient to ensure the flow does not separate.

A reduction in dirt deposition is obtained for vehicles with sharp edges, mainly because the air remains attached around the corner and, therefore, the air speed near to the surface is greater. This will be augmented by the jet of air exhausted from the space between the vane and the body, which is the only mechanism responsible for a reduction in the dirt deposition on vehicles with rounded edges. This increases the air speed adjacent to windows and cab sides, thereby helping to prevent dirt sticking to the vehicle sides.

Container front fairing

Front edge fairings on the container prevent (or at least limit) flow separation on the roof of the container and sides, which would otherwise lead to high drag values.

Rear-end tapering

Tapering the rear of the container section effectively increases the pressure acting on the rear face of the vehicle (although this is still less than that on the front face) and reduces the area on which this pressure acts. The result is a reduction in drag force.

Rear mud flap

In the absence of an air dam, the front of the spray guard represents a region of relatively high pressure, while the pressure acting on the rear of the spray guard is at a (lower) level similar to that acting on the remainder of the rear of the vehicle. The net effect is an increase in drag. If an air dam is also used, the low pressure generated behind it may reduce the pressure on the front face of the spray guard, thereby limiting these adverse effects to some degree.

Other protuberances

To offer minimum additional drag, protuberances should be located in a region of recirculating flow, as the mean air speed in such regions is well below that in the external flow field. Close to the stagnation point on the front of the vehicle, the air speed is also relatively low and, typically, the shapes to be attached are oriented such that their drag coefficient for a given flow speed is reduced.

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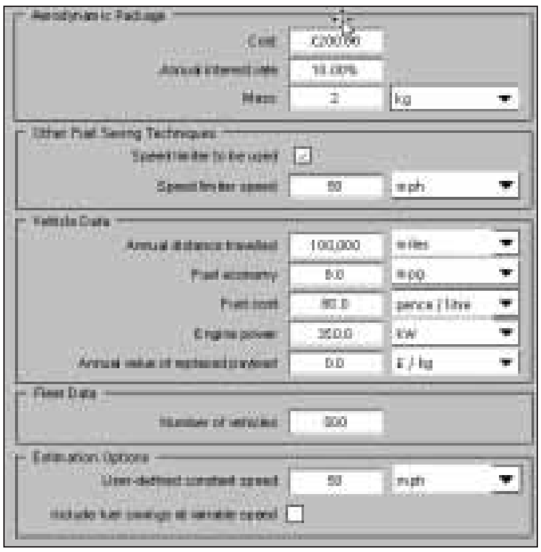
B SPREADSHEET INSTRUCTIONS

B.1 Introduction

The computer program on the disc in the pocket at the back of the Guide will enable you to gain a more quantitative understanding of the ‘real-world’ benefits of aerodynamic modifications possible on commercial transport vehicles. The program takes the details of the typical journey parameters for a particular fleet vehicle and estimates the savings possible through aerodynamic refinements or careful speed-limiting measures, automatically incorporating the appropriate changes in gearing. Another useful feature of the program is the facility to investigate how much your current aerodynamic package or its operational use affects your fleet’s fuel economy. For example, it is not uncommon for cab-top fairings and deflectors to be in their raised position even in the absence of a trailer; by using the program you will be able to evaluate the additional costs that result from this.

The program has been designed in the form of a spreadsheet that will run on most personal computers using Microsoft® Windows 95, 98 or NT operating systems and either the Microsoft® Excel 95 (or later versions) or Lotus 123® spreadsheet software packages. To use the fuel economy estimator program, turn on your computer and log-on to Windows®, insert the 3.5 inch ‘floppy’ disc supplied into the disc drive of your computer, open your spreadsheet package (Microsoft® Excel or Lotus 123®) and select **File - Open** and then **A:** from the pull-down list of available drives. The spreadsheet is called **‘Savings.xls’.** The program consists of two user-accessible ‘worksheets’ labelled **Input Data** and **Results**, which are described in detail below. Please refer to your computer’s user manual if you encounter any difficulties running the spreadsheet software applications.

B.2 Input Data



This worksheet is split into several sections that enable you to enter the information describing your fleet and its operation. Just enter the required numbers into the boxes and, where necessary, select the appropriate units from the drop-down menus to the side.

The first box asks for the total cost of purchasing and fitting the chosen aerodynamic package and also for its mass so that it can be included in the gross vehicle weight.

The program can also evaluate the additional fuel savings to be found by careful speed-limiting

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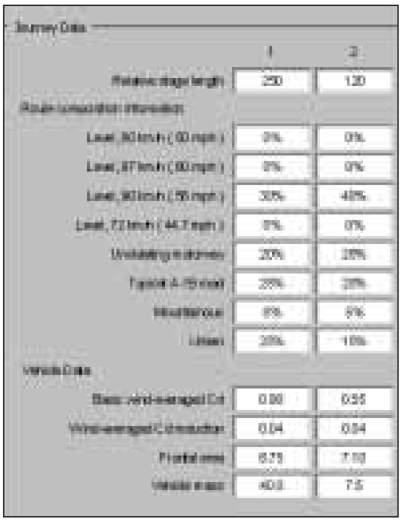
alone or in conjunction with aerodynamic modifications. If speed limiting is already used on your vehicles, then do not select this box. Instead, enter the value to which the limiter is set in the **user-defined constant speed** box.

The next step is to specify the typical current operational details for an example vehicle and the number of these vehicles in your fleet. At this stage, it is important to include the effective commercial value of any transporter space that may have been sacrificed to implement the chosen aerodynamic modifications. This is used in conjunction with the mass of the package above to determine any loss of revenue. If the normal cruising speed of your vehicle is not already listed in the Journey data section, there is an option to enter it here. This will then update the first of the speed options on the right-hand side of the page.

The right-hand side of the **Input Data** screen contains two main sections: first, a description of the typical journey profile to be undertaken; second, the aerodynamic modifications that have been made to the vehicle. Here, the user can specify the proportions of a particular journey made up by various road speeds and conditions for each of up to four stages, two of which are illustrated here. This flexibility allows the fuel savings to be calculated for compound journeys, such as outward and return travel by different routes, or multiple delivery locations.



When specifying the relative stage lengths of a multi-element journey, you can enter either the approximate actual distance covered in each stage or just the rough proportions between them. Also, it is important to include changes in vehicle mass, frontal area and baseline drag values between different stages of a journey if there is a different trailer, the loading is changed or the trailer removed completely.

The different route composition options can be considered as two groups: a range of standard cruising speeds (the first of which can be set by the user as described at the bottom of the previous page) and a list of several road conditions over which the vehicle speed would naturally vary. In these situations, it is impossible to quantify all the factors that would affect the fuel economy, so they have been omitted from the calculations. However, as mentioned earlier in this Guide, the technique of the driver becomes a more important consideration in these circumstances.

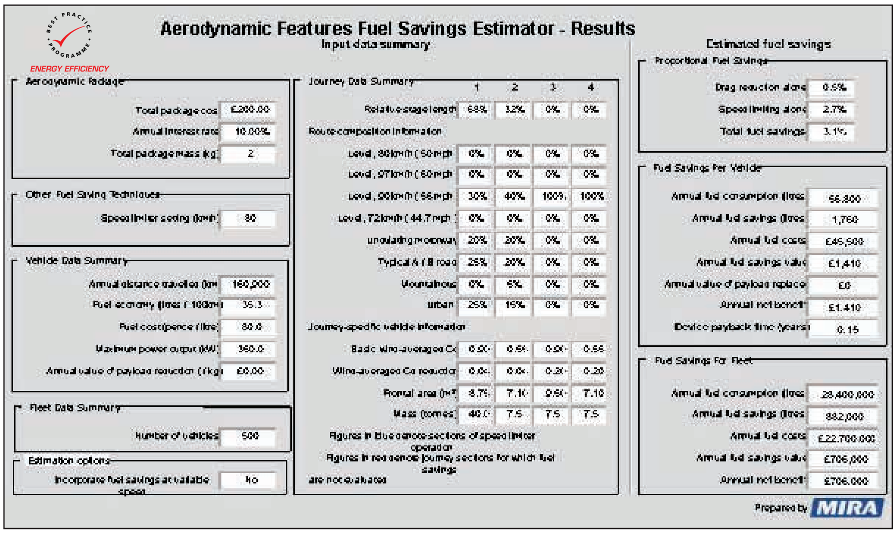
The summary tables in Sections 2.1 and 3.4 list baseline aerodynamic drag values and frontal areas for each main type of vehicle, and also the drag reductions achievable from the modifications available. These baseline values are averages for each vehicle type. Some model variants can differ significantly from these figures, so it is best to check with the vehicle manufacturer what the drag coefficient is for your particular vehicle. Then, simply enter the appropriate baseline drag for your vehicle, including the reduction from any aerodynamic package you already have, and subtract the drag reduction offered by the modifications under consideration. Remember to take into account the variations that come about through interference between some measures, as already described in this Guide. Note that you can enter ‘negative’ Cd reductions to see the consequences of adverse features or combinations of features.

In this example, an articulated vehicle making multiple deliveries (Stage 1) travels for 50% of its outward journey on a motorway with a standard limited speed of 50 mph, but with 30% of this on level road and 20% at a reduced speed up and down the shallow hills of an undulating motorway. A further 25% of the outward journey is along level A/B roads and the other 25% through urban areas. Stage 2, the return leg, is made without a trailer and is approximately half as long, but involves greater proportions of level motorway travel.

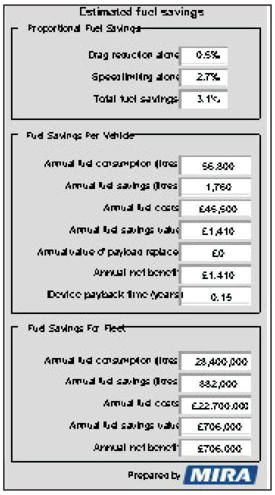
The input data for the example shows how the vehicle mass, reduction in drag, and frontal area have changed on the return journey to account for the changes in the vehicle set-up and loading. In this example, we have entered the actual distances covered in each leg, although we could have just put 2 and 1 in the first two **Relative stage length** boxes as the outward journey is roughly twice the length of the return. Also, for the sake of simplicity, we have chosen to omit the additional savings accrued at variable speed.

B.3 Results

The **results** page consists of a summary of the input data (for easy reference) and a breakdown of the fuel savings that could be achieved by implementing the aerodynamic and speed-limiting modifications on both an individual vehicle and the fleet as a whole. The input data are summarised across the left and centre of the page. The spreadsheet re-scales input values where appropriate, so this section enables you to check whether all your input details are as intended. This also means that, as all the input details are summarised here, this is the only page you need to print out to have a hard-copy record of your predictions.



The program takes the input data and estimates the savings possible through implementing the speed-limiting and aerodynamic changes, both individually and in conjunction with one another. These are presented as percentages of the projected annual fuel usage based on the input annual mileage and fuel prices.



The **Fuel savings per vehicle** box illustrates these savings in real terms. It presents a breakdown of the actual quantity and value of fuel saved. An estimated net annual benefit per vehicle takes into account the value of any payload space sacrificed for the modifications. An estimate of the time it would take to pay back the initial investment on the modifications, purely out of the money saved by them, is also provided.

The actual value of the total benefit of the fuel saving modifications is given at the bottom of the column. The example results shown are based on a medium to large fleet of 500 vehicles, but it is clear that there are substantial savings to be made whatever the size of your fleet.

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